AGE-RELATED CHANGES IN RESOLVING PROACTIVE INTERFERENCE IN ASSOCIATIVE MEMORY

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AGE-RELATED CHANGES IN RESOLVING PROACTIVE INTERFERENCE IN ASSOCIATIVE MEMORY

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For Astra, to give you a better life.

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SUMMARY

Previous research has found that older adults are more susceptible to proactive interference. This is likely due to age-related deficits in the PFC-mediated cognitive control processes recruited to resolve interference. The current functional magnetic resonance imaging (fMRI) study investigated if age-related deficits in PFC-mediated cognitive control processes underlie age-related differences in the resolution of proactive interference in an associative memory task. Young and older adults were tasked with remembering which associate (face or scene) objects were paired with most recently during study, under conditions of high, low or no proactive interference. Following scanning, participants' memory was tested for varying levels of episodic detail about the pairings. Young and older adults were similarly susceptible to proactive interference. Memory for both the general target category and the specific target associate worsened as the level of proactive interference increased, with older adults having moderately worse memory for the specific target associate. Across age, the left-VLPFC showed increased recruitment for increasing levels of interference at encoding suggesting that older adults are able to spontaneously engage in post-retrieval selection to the same extent as young adults. At retrieval, older adults recruited the vmPFC more than young adults during remembered low interference trials but similarly recruited the vmPFC during remembered high interference trials. In line with the CRUNCH model, this suggests that older adults need to engage in more monitoring for low interference items, but engage in a similar amount of monitoring to young adults for high interference items, suggesting that successfully resolving high interference is equally difficult for both young and older adults.

CHAPTER 1. INTRODUCTION

It is well established that advancing age is associated with declines in a number of cognitive functions. Perhaps the most noticeable cognitive declines are seen in episodic memory tasks, specifically associative memory. Associative memory is the ability to learn and remember the relationship between multiple items, such as people, events, objects, and places. Numerous imaging studies have suggested these age-related impairments are due to dysfunction in brain regions that support associative memory, specifically the medial temporal lobe (MTL) and the prefrontal cortex (PFC). The MTL consists of the hippocampus and parahippocampus and constitutes a large part of the "core episodic network" (Benoit & Schacter, 2015). The MTL has been implicated in the facilitation of both encoding and retrieval. During encoding, the MTL helps to create unique memory representations through the binding of multiple features and during retrieval, the MTL facilitates the comparison of those representations with retrieval cues (Eichenbaum, Yonelinas, & Ranganath, 2007; Sestieri, Shulman, & Corbetta, 2017; Simons & Spiers, 2003). Generally, older adults' impaired memory performance is thought to be due to their under-recruitment of these regions relative to young adults (Cansino et al., 2015; Dennis, Kim, & Cabeza, 2008). However, evidence demonstrating that older adults recruit the MTL to the same extent as young adults when task performance is matched (Angel et al., 2013; de Chastelaine, Mattson, Wang, Donley, & Rugg, 2015, 2016; Rugg & Morcom, 2005) suggests the MTL is not the major contributor to the age-related impairments seen in associative memory. Rather, it is more likely that these age-related impairments are due to PFC dysfunction.

Perhaps the most popular theory to explain this dysfunction is the "frontal aging hypothesis", which suggests that the PFC is selectively impacted by age-related deterioration, resulting in earlier declines in frontal-dependent functions than frontal-independent functions (Greenwood, 2000; West, 1996). These frontal-dependent processes include attention, decision-making, inhibitory control and top-down modulation. Together, these processes are termed cognitive-control processes, or executive functions. Cognitive-control processes allow for the adaption of information processing and behavior to meet current task goals (Miller, 2000). Specifically, in associative memory, cognitive-control processes allow for the binding of item relations and their subsequent successful retrieval. Support for this hypothesis comes from a number of studies showing more age-related declines in white- and grey-matter volume in the PFC than other regions (Nyberg et al., 2010; Raz et al., 1997; Raz & Kennedy, 2009), along with studies showing age-related declines in PFC activity during both encoding (Dennis, Hayes, et al., 2008; Dulas & Duarte, 2011) and retrieval (Duarte, Henson, & Graham, 2008; Dulas & Duarte, 2012b; McDonough & Gallo, 2013a), despite age-equivalent MTL recruitment. However, as the PFC is quite a large region supporting a number of processes, the "frontal aging hypothesis" seems to be too generalized, as it fails to predict individual differences in the various regions in the PFC and the cognitive-control processes they mediate.

1.1 Proactive Interference

Such processes include those recruited during proactive interference. Proactive interference is when previous, but no longer valid, information interferes with the retrieval of new information. For example, misremembering your new medication dosage may be due to a strong memory of your previous medication dosage. Previous research suggests

that older adults are more susceptible to proactive interference than young adults. They have impaired performance, relative to young adults, across a number of domains: working memory (Bowles & Salthouse, 2003; Emery, Hale, & Myerson, 2008; Jonides et al., 2000; Lustig & Jantz, 2015; Lustig, May, & Hasher, 2001; May, Hasher, & Kane, 1999; Pettigrew & Martin, 2014), episodic memory (McDonough & Gallo, 2013b; Wahlheim, 2014) and long-term memory proactive interference tasks (Healey, Hasher, & Campbell, 2013; Ikier, Yang, & Hasher, 2008). One domain that has not been thoroughly investigated is older adults' susceptibility to proactive interference in associative memory. In the existing literature, some have found older adults perform similarly to young adults (Dulas & Duarte, 2016; Guez & Naveh-Benjamin, 2016), while others have found older adults perform worse than young adults (Burton, Lek, Dixon, & Caplan, 2019; Ebert & Anderson, 2009; Jacoby, Bishara, Hessels, & Toth, 2005). One goal of the present study is to paint a clearer picture of older adults' susceptibility to proactive interference in associative memory.

Previous research has indicated that two main cognitive-control processes are needed to successfully overcome proactive interference: post-retrieval selection and post-retrieval monitoring. The first is a process that resolves competition between multiple active representations (for review, Badre & Wagner, 2007; Fletcher, Shallice, & Dolan, 2000; Moss et al., 2005). Specifically, after the information is retrieved, relevant information is enhanced and irrelevant information is suppressed. With the medication example, it is likely that you retrieved both the old dosage and the new dosage. In order to resolve this, you must suppress the old, irrelevant dosage, and enhance the new, relevant dosage. Older adults' poor performance on proactive interference tasks may be due to a failure to engage this selection process and this is likely due to age-related deficits in inhibitory processing.

Various studies have demonstrated older adults' failures to inhibit irrelevant information in both reading comprehension and memory-related retrieval tasks (Connelly, Hasher, & Zacks, 1991; Hartman & Hasher, 1991; Hasher, Quig, & May, 1997). In that inhibitory processing is a seemingly important component of post-retrieval selection, it is conceivable that older adults' increased susceptibility to proactive interference is due to their attention being captured by strong memories for the irrelevant information, resulting in increased errors.

The second of these main processes, post-retrieval monitoring, evaluates and manipulates the retrieved information when someone is close to their decision criterion; specifically, relevant information is considered in relation to the decision to be made (R. N. Henson, Rugg, Shallice, & Dolan, 2000). Behavioral studies have shown that older adults have worse performance on tasks that place high demand on post-retrieval monitoring, suggesting that they are less able to engage this process (for review, Mitchell & Johnson, 2009). Though there is evidence that both selection and monitoring are needed to resolve proactive interference, the exact mechanisms by which they operate, alone or in relation to one another, are still unclear. This study aims to disentangle the neural mechanisms behind these processes and elucidate how they are affected by age.

1.2 The Role of the DLPFC and VLPFC in Resolving Proactive Interference

Numerous neuroimaging studies have found evidence that post-retrieval selection is mediated by the left mid-ventrolateral prefrontal cortex (VLPFC) (for review, Badre & Wagner, 2007). Both lesion (Thompson-Schill et al., 2002) and transcranial magnetic stimulation studies (Feredoes, Heinen, Weiskopf, Ruff, & Driver, 2011; Wais, Kim, &

Gazzaley, 2012) have indicated that disruption of the left mid-VLPFC results in longer response times and a higher percentage of errors in proactive and semantic interference working memory tasks. In a semantic interference task using the short-term Deese-Roediger-McDermott (ST-DRM) paradigm, young adult participants were shown four words that were all associated with a common unstudied theme word (Atkins & Reuter-Lorenz, 2011). After solving a math problem, participants were presented with a probe word and asked to respond with whether or not the probe was in the previously studied set of four words. The probe could be one of three options: the unrelated lure, a theme word not associated with the presented list; the related lure, a theme word associated with the list; or the positive probe, a word in the list. Consistent with previous studies, related lures were associated with greater activation in the left mid-VLPFC than unrelated lures. Interestingly, this region showed a similar increase in activity for false alarms and correct rejections of related lures, suggesting that it does not distinguish interference that is resolved correctly or incorrectly. Furthermore, response times were found to be slower for trials with high interference (i.e., to related lures) than low interference (i.e., to unrelated lures). Individual differences in this increase in response time correlated with percent signal change in the left mid-VLPFC between related and unrelated lures. Along with other neuroimaging evidence that the left mid-VLPFC is recruited proportionally with increasing levels of interference (for review, Badre, 2008; Nelson, Reuter-Lorenz, Persson, Sylvester, & Jonides, 2009), these results suggest that this region is sensitive to the level of interference, but not to the successful resolution of interference.

As previously mentioned, there is an abundance of research suggesting age leads to disruptions in PFC-mediated processes, however, there is little research on the effect of age

on VLPFC-mediated post-retrieval selection. To the best of our knowledge, only two previous fMRI study have investigated age-related changes in the VLPFC during the resolution of proactive interference (Dulas & Duarte, 2016; Jonides et al., 2000). In the Jonides (2000) working memory study, both young and older adults were presented with a set of four target letters. Following a short retention period, they were then presented with a single probe letter and asked to respond with whether or not the letter was in the previously presented set. The probe letter was either a letter found in the previous set of target letters (high interference) or a letter not found in the previous two sets of target letters (low interference). Consistent with previous behavioral studies older adults were disproportionately affected by interference: they had slower response times and lower accuracy than younger adults for the high interference than low interference trials. Young adults, relative to older adults, were found to have greater activation in the left-VLPFC for high interference than low interference trials. These results suggest that older adults' under-recruitment of the left-VLPFC could be due to their failure to engage in post-retrieval selection, which is likely due to their increased susceptibility to proactive interference.

Neuroimaging studies have indicated that post-retrieval monitoring is supported by the bilateral dorsolateral prefrontal cortex (DLPFC) (Achim & Lepage, 2005; Fletcher & Henson, 2001; R. N. Henson et al., 2000; R.N. Henson, Shallice, & Dolan, 1999; Lepage, Brodeur, & Bourgouin, 2003; Mitchell, Johnson, Raye, & Greene, 2004; Rugg, Henson, & Robb, 2003; Shallice et al., 1994). One fMRI study investigated the role of the DLPFC in post-retrieval monitoring in both an item recognition and an associative recognition task (Achim & Lepage, 2005). Young adult participants underwent four scanning runs alternating between encoding and retrieval. During study, they were presented with stimuli

either individually (item encoding) or in pairs (associative encoding). In order to dissociate item and associative memory, participants were required to make two different memory decisions at test. If participants were presented with a single stimulus, they were asked to make an old/new decision and if they were presented with a pair of stimuli, they were asked to decide whether the stimuli in the pair were intact (same images in the pair shown at encoding) or rearranged (images from previous pairs shown at encoding were presented in new pairs). Activation in the DLPFC was greater for old than new trials in the item recognition task and rearranged than intact trials in the associative memory task, suggesting trials requiring greater post-retrieval monitoring are associated with greater DLPFC activation. As this study only included correct rejections in the analyses, researchers were not able to investigate the role the DLPFC plays in successfully resolving interference. However, the previously mentioned Atkins (2011) study found that the DLPFC, but not the VLPFC, showed greater activation for correct rejections than false alarms for related lures (Atkins & Reuter-Lorenz, 2011). Taken together, these results suggest that both post-retrieval monitoring and post-retrieval selection are needed to overcome proactive interference. However, post-retrieval monitoring may play a more critical role in successfully overcoming proactive interference by mediating successful post-retrieval selection.

The findings of age-related changes in DLPFC-mediated post-retrieval monitoring are mixed: some studies have found that older adults under-recruit the DLPFC relative to young adults (Dulas & Duarte, 2012a; Friedman, 2000; Paxton, Barch, Racine, & Braver, 2008), while others suggest that when group differences in performance are controlled for, older adults recruit this process similarly to young adults (Dulas & Duarte, 2013; Li,

Morcom, & Rugg, 2004). These findings suggest that under certain circumstances, older adults may not be able to recruit post-retrieval monitoring to the same extent as young adults. It is possible that this is the same for VLPFC-mediated post retrieval selection: older adults may be able to recruit the VLPFC to the same extent as young adults when performance between age groups is matched, but when older adults' performance is impaired relative to young adults, they may not.

1.3 Motivation for the Current Study

In a previous study, we investigated age-related changes in the PFC-mediated cognitive control processes recruited during the resolution of proactive interference (Dulas & Duarte, 2016). Specifically, we aimed to identify if older adults are actually more susceptible to proactive interference in associative memory retrieval and to distinguish the roles the DLPFC and VLPFC play in resolving proactive interference. In this task, young and older adults studied objects paired with associates (either a face or scene) with varying levels of interference. In the low interference condition, the object was paired with the face (target) four times and the scene (lure) once. In the high interference condition, the object was paired with the face (target) twice and the scene (lure) three times. Participants were instructed before the encoding phase that they would be immediately tested on the last set of pairings. The retrieval phase, which was scanned, was a two-staged forced-choice paradigm that included old and new objects. Participants first made an old/new decision, then selected which of two associates was paired with the object most recently. Correct rejection trials were used as the baseline, as there should be little to no post-retrieval monitoring or post-retrieval selection during these trials.

Proactive interference impaired associative memory accuracy equally for the young and older adults. Across age groups, associative memory accuracy was better for low than high interference items. Unsurprisingly, we found no effect of interference for item memory. Across age groups, there was no difference in item memory accuracy between low and high interference items. For both associative memory accuracy and item memory accuracy, young adults performed marginally better than older adults. For both groups, the left-VLPFC showed more activation for high than low interference trials. Most participants did not have enough low interference incorrect trials to analyze, so we were only able to look at accuracy for the high interference trials and found no difference between correct and incorrect trials. Consistent with previous research, these results suggest that the left-VLPFC is sensitive to the level of interference, but does not directly contribute to accurate memory retrieval. The left- DLPFC, however, was sensitive to associative memory accuracy, but in the young adults only. This could suggest that young adults are more likely to engage in post-retrieval monitoring, however, we don't believe this to be the case as we only found a marginal age-group difference in associative memory accuracy. It is more plausible that the left-DLPFC is not the sole contributor to the successful resolution of proactive interference, but rather is part of a network of regions that contribute to post-retrieval monitoring. Another possibility is that older adults did not encode the lures, thereby reducing demands on post-retrieval monitoring leading to under-recruitment of the DLPFC. We will attempt to determine which of these possibilities is most plausible in the present study.

It is important to mention a few limitations of this study that could have led to these results. The two-stage forced-choice design employed in the test phase posed some issues.

For one, because we did not separately test for item and associative memory recognition, they could not be fully dissociated. Another issue was the correctly rejected new items used as a baseline differed from the interference items both in level of interference and novelty. Furthermore, associative memory decisions could have been based on familiarity rather than recollection. As we presented participants with images of a face and a scene associate, it is possible that by seeing the particular associate, they chose that associate because they more familiar with it rather than actually recollecting that the object had been paired with that specific associate. If this is the case, there would have been minimal demands placed on interference resolution, resulting in less recruitment of the PFC-mediated cognitive control operations. This could also explain the marginal difference in associative memory accuracy between young and older adults, as older adults have been found to have similar memory accuracy to young adults when retrieval is based on familiarity rather than recollection. Finally, as we did not scan the study phase, we cannot be sure that the older adults encoded the lures. Thus, if they did not encode the lures to the same extent as the young adults, there would have been less interference at retrieval.

In the current study, we addressed these limitations with the hope of discovering a clearer image of the effect of age on the PFC-mediated cognitive control processes recruited during the resolution of proactive interference. We employed a similar paradigm as the one used in our previous study. Young and older adults again studied objects paired with associates (either a face or scene) with varying levels of interference. In order to solve the baseline limitation, we introduced a new, no interference condition at encoding. In this condition, the object was paired with the target for all of the encoding blocks. Thus, the baseline condition was matched with the other interference conditions both on novelty and

interference. Since we no longer have a need for new items, we only tested participants on the old, studied items at retrieval. This eliminated our previous limitation of dissociating item and associative memory. Furthermore, we changed the two-staged forced-choice retrieval decision to now have participants decide which associate category (i.e. face vs scene) the object was most recently paired with rather than having them decide between two images. This reduced the possibility that memory decisions are based on familiarity rather than recollection. We also introduced a new task at the end of retrieval, a post-retrieval test, to measure the specificity of participants' memories of the pairings. This post-retrieval test allowed us to investigate the contribution of recollection to their memory decisions. Asking participants for the general category of the associate utilizes familiarity, while asking for the specific associate requires more recollection. Thus, this additional test allowed us to address the marginal age difference in associative memory accuracy found in our previous study. In this task, the participants were again tested on the pairings from the fourth block of encoding, but were asked questions with increasing specificity. For example, if they responded that the object was paired with a face, they were then required to respond with the gender of the face and to then choose which specific face was paired with the object. Given the time constraints on how long a participant can be in the scanner, the post-retrieval phase was not scanned.

Behaviorally, we predict that older adults will have worse memory performance than young adults, specifically under conditions of high interference. Memory performance across groups will show a graded pattern among interference, such that memory performance should be highest for no interference trials and lowest for high interference trials. Alternatively, it is possible that due to our engaging encoding task, older adults may

perform similarly to young adults on our retrieval task, as was found in our previous study. Regardless of age-differences on our retrieval task, we predict that for our post-retrieval task, young adults will have higher percentage of correct specific memory responses (i.e. they correctly remember the exact associate the object was paired with) than older adults, as older adults have been found to perform similarly to young adults on tasks that rely on familiarity, but not recollection. Specific memory performance will also show a graded pattern among interference, such that specific memory performance will be highest for no interference trials and lowest for high interference trials. This will again be across groups, with older adults having disproportionately worse memory performance for the specific high interference trials.

With regard to our imaging analyses, we used both univariate and multivariate pattern analyses (MVPA) to address our questions of interest. Univariate analyses were used to assess the roles of the VLPFC and DLPFC in post-retrieval selection and post-retrieval monitoring, respectively. MVPA was used to get a better understanding of the underlying mechanisms of proactive interference. MVPA has been used in a number of studies to investigate patterns of neural reactivation. It is suggested to be a good technique because rather than averaging across voxels to assess average activity within a cluster, like in univariate analyses, MVPA uses coactivating patterns of activity across voxels within and across regions (Norman, Polyn, Detre, & Haxby, 2006). This in turn allows us to analyze various brain states in an area and how these brain states retrieve different types of information (Haxby, 2012). In the present study, we used MVPA to examine if old associations (lures) were reliably reactivated during attempts to recover recent ones

(targets) in both age groups and if the relative amount of target vs. lure reactivation differed as a function of mnemonic interference, memory performance and age.

CHAPTER 2. METHOD

2.1 Participants

The participants for this study were 25 young adults (13 females, ages 18-37) and 25 older adults (12 females, ages 60-75). Older and younger adults had no difference in level of education [$t(48) = .413$, $p = .681$]. Group characteristics are presented in **Table 1**. Three young adults and five older adults' data were not included because they terminated the study early due to being uncomfortable in the scanner. An additional two young adults and three older adults' data were not included due to technical issues. All participants were recruited from the Georgia Institute of Technology and the surrounding Atlanta area. All participants were right-handed, native English speakers, with normal or corrected to normal vision (using MRI-compatible glasses when necessary), and with no reports of psychiatric/neurological disorders, vascular disease, or psychoactive drug use. Individuals taking CNS-active medications or antihypertensive medications were excluded from participation. Prior to participation, fMRI eligibility was assessed. Due to potential fMRI safety hazards for some individuals, those who were claustrophobic, pregnant, or had implanted ferromagnetic materials and certain medical devices were excluded. Participants were compensated with class credit or $15 per hour. All participants signed consent forms approved by the Georgia Institute of Technology Institutional Review Board.

Table 1 - Group Characteristics

Measure	Young (n = 25)	Older (n = 25)
Age	24.44 (5.37)	67.04 (4.44)
Sex	13 females	12 females
Education	15.64 (2.23)	15.92 (2.55)
MoCA	27.68 (1.81)	26.52 (2.77)

Note: Standard deviations in parentheses.

2.2 Neuropsychological Assessment

After completing the fMRI portion of the study, participants were administered the Montreal Cognitive Assessment (MoCA) (Nasreddine et al., 2005) to rule out any cognitive impairments, such as mild cognitive impairment. A score of less than 26 out of 30 is the traditional cutoff score for the MoCA. However, the MoCA has been found to not fairly assess the cognitive status of people from different educational, cultural, and racial backgrounds (Carson, Leach, & Murphy, 2018; Manly, 2005; Sink et al., 2015). Due to this, we did not exclude participants who scored lower than 26 on the MOCA but scored within two standard deviations of mean performance on our experimental task. Three young adults who were already familiar with the test were excluded from testing. Average MoCA scores are presented in **Table 1**. Older adults had moderately lower scores on the MoCA than young adults [$t(45) = 1.676$, $p = .101$].

2.3 Materials

Two-hundred and sixteen color photographs of nameable objects taken from Hemera Technologies Photo-Objects DVDs, or from the Internet via Google search were used. All images were presented against a grey background. There was no overlap of multiple objects depicting the same object. In addition, eight images of young adult faces (four male, four female) and eight images of scenes (four indoor, four outdoor) were used as associates for the experiment. The faces were taken from the Max Panck Institute's FACES database (Ebner, Riediger, & Lindenberger, 2010) and the scenes were taken from the SUN database (Xiao, Hays, Ehinger, Oliva, & Torralba, 2010).

2.4 Procedure

The study was divided into three phases: encoding, retrieval and post-retrieval. A practice session was administered before each phase to ensure the participant understood the task. The practice session for retrieval was administered before the encoding phase to ensure the participant could sufficiently perform the memory task before entering the scanner. Only the fourth block of encoding and retrieval were scanned. Stimuli were counterbalanced across participants, such that each object appeared in different conditions across participants. 216 objects were studied during encoding and all 216 objects were later tested at retrieval and post-retrieval. **Figure 1** displays the experimental design.

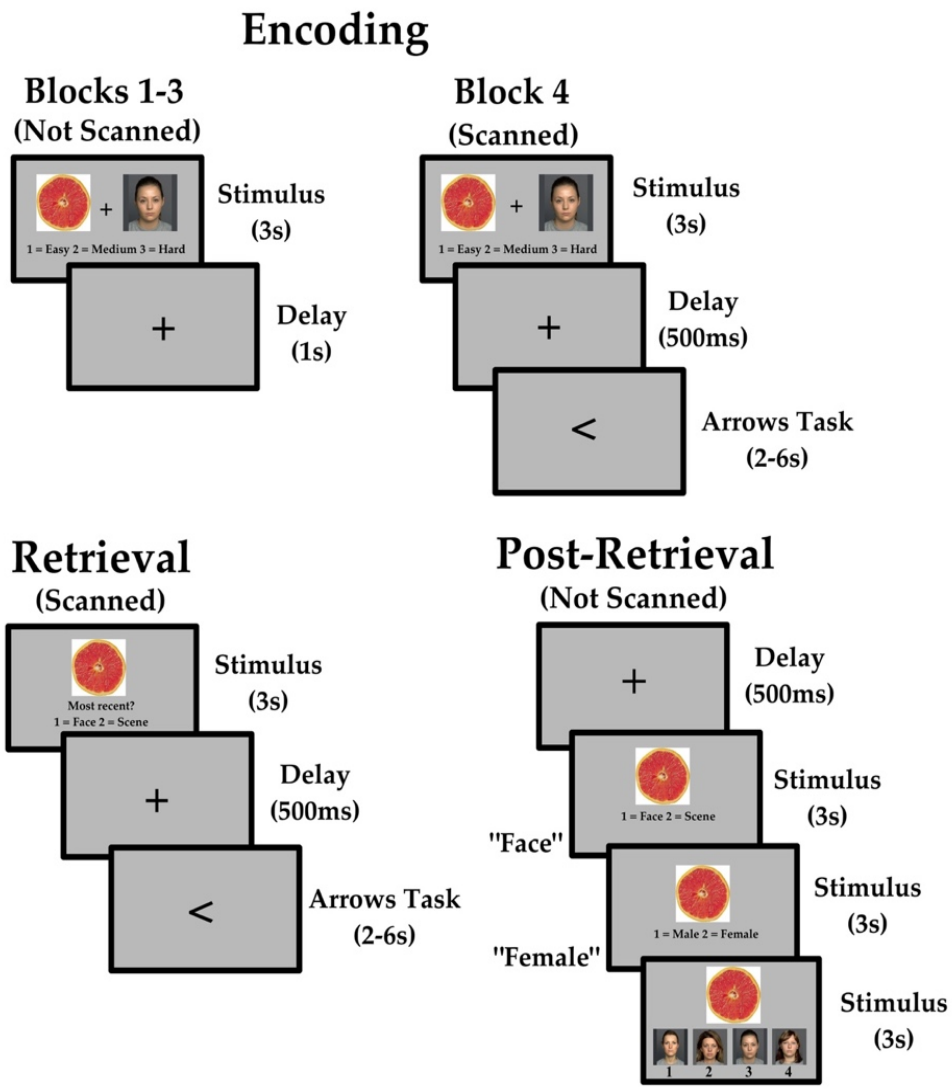

Figure 1 - Experimental Design for the study.

2.4.1 Encoding

The encoding phase was separated into four blocks: the first three were administered outside the scanner and the fourth was administered inside the scanner. The fourth block was scanned in order to train the classifier for MVPA to distinguish between patterns of activity for faces and scenes. Participants were presented with all 216 objects in each block. For each trial, the participant was presented with an object and either a face

or a scene for 3000 ms. For half of the participants, the object was presented on the left side of the screen and the face/scene on the right. For the other half of the participants, this was reversed. The participants were asked to rate how easy or hard it is to imagine the images together. While the pairing was presented on the screen, they were asked to respond with their rating using a number pad: "1" if it is easy to imagine the images together, "2" if it is neither easy nor difficult to imagine the images together and "3" if it is difficult to imagine the images together. While in the scanner, participants responded on a button box with the same response options. For the first three blocks, each trial was followed by a fixation cross for 1000 ms. For the fourth block, each trial was followed by an arrows task. The arrow task maximizes design efficiency by pseudorandomly interspersing event trials with "active" baseline trials lasting between 2 and 6 s, jittered in increments of 2 s (Dale, 1999). Every 2 s, an arrow appeared on the screen and participants were asked to respond using a button box to indicate the direction of the arrow: "1" in response to a left pointing arrow and "2" for a right pointing arrow. Requiring participants to respond to the arrows kept them engaged in the task and minimized default mode network activity (Stark & Squire, 2001). Immediately following the completion of the first three blocks, participants were taken to the scanner to complete the rest of encoding and retrieval. Each block was pseudorandomized so participants were not presented with more than three trials of the same condition (i.e. high interference, low interference, no interference) in a row. The first three blocks lasted 45 min, with each block lasting 15 min. The fourth block was split up into three parts in order to give the participant frequent breaks to prevent fatigue; each part lasted 9 min for a total of 21 min. The total duration of the encoding phase, including practice and set-up in the scanner, was 1.5 hrs.

As seen in **Figure 2**, during encoding, objects were evenly divided across the high interference, low interference and no interference conditions (72 objects per condition). Unfortunately, due to a coding error 18 young adults and 25 older adults only had 60 objects in the low interference condition. For the high interference condition, the object was paired with one of the associates (e.g. a face) for the first two blocks and paired with another associate (e.g. a scene) for the last two blocks. For example, a image of an avocado may be paired with a image of a kitchen for the first two blocks and then a image of a male's face for the last two block. Thus, at retrieval, there was a strong association between the object and the most frequently paired associate (e.g. the kitchen) creating a high level of interference. For the low interference condition, the object was paired with one of the associates (e.g. a face) for three blocks and paired with another associate (e.g. a scene) for one other block. The final time the object was viewed, during the fourth block, it was paired with the target associate (e.g. a scene). For example, a image of a passport may be paired with a female face for the first block, then paired with a image of a mountain for the second and third and fourth block. Thus, at retrieval, there may be some interference between the mountain and the female face. For the no interference condition, the object was paired with one of the associates (e.g. a face) for all four blocks. Thus, at retrieval there will be a strong association between the object and the paired associate, with there being no interference.

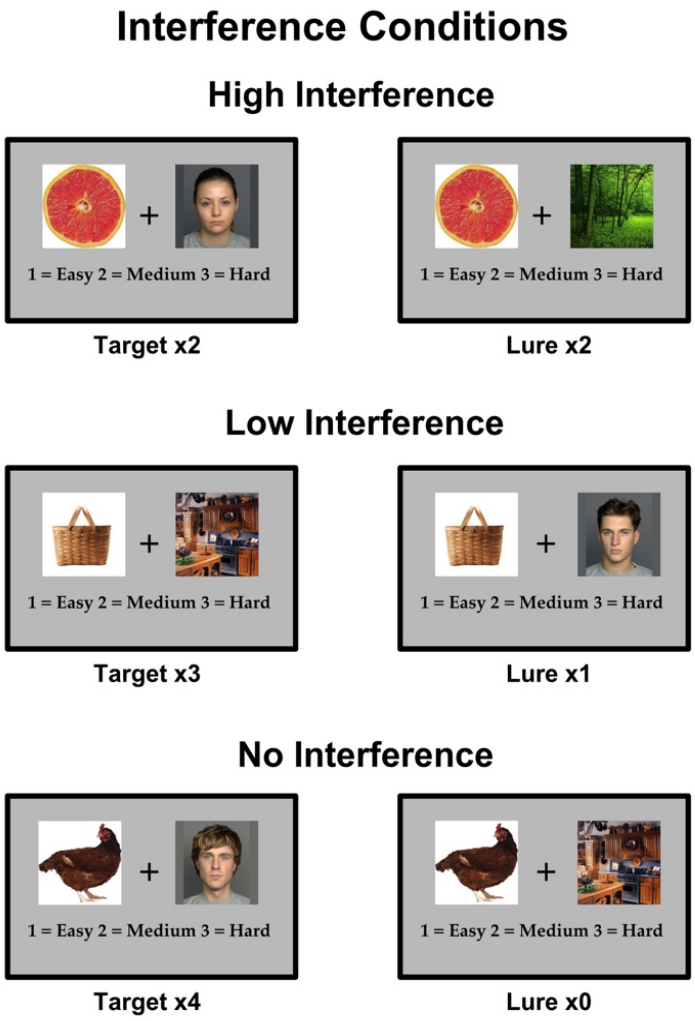

Figure 2 - Examples of each interference condition are shown. The numbers indicate the number of times, across blocks, the object is paired with either the target or lure associate. The target is always presented in the fourth block.

2.4.2 Retrieval

After finishing the fourth block of encoding in the scanner, participants immediately began the retrieval phase. Participants were tested on all 216 studied objects. Retrieval was divided into three blocks, each consisting of 72 trails. For each trial, participants were presented with an object in the center of the screen. Directly under the

object, the participants were presented with “Most Recent?” and their response options. While the object was presented on the screen, they were asked to decide what the object was most recently paired with (i.e. in the fourth block of encoding). Half of the participants were asked to respond with “1” if the object was most recently paired with a face and “2” if the object was most recently paired with a scene. For the other half of the participants, the response options were reversed. Each trial was followed by the arrow’s task lasting 2s-6s. Each block was pseudorandomized so the participants were not presented with more than three trials of the same condition (i.e. high interference, low interference, etc.) in a row. Each block lasted nine minutes for a total of 21 minutes.

2.4.3 Post-Retrieval

After exiting the scanner and completing MoCA, participants began the post-retrieval phase. Participants were again tested on all 216 studied objects. The post-retrieval test was given to assess the specificity of the participants’ memories of the pairings. Given time constraints of how long we can comfortably keep a participant in the scanner, the post-retrieval test was not administered in the scanner. Again, this task was divided into three blocks, each block consisting of 72 trials. For each trial, participants were presented with an object in the center of the screen. While the object was presented on the screen, they were asked to decide what the object was most recently paired with (i.e. in the fourth block of encoding). Half of the participants will be asked to respond with “1” if the object was most recently paired with a face and “2” if the object was most recently paired with a scene. For the other half of the participants, the response options were reversed. We asked the participant this question again to ensure that trials for which specific targets are selected are based on recollection. That is, responses that changed between retrieval and post-

retrieval most likely reflect poorer memory quality than those that are consistently accurate. Following the first question, we asked participants what specific category the object was last paired with. For example, if the participant responded with "Face" for the first question, we then asked them to respond with "1" if it was a male face and "2" if it was a female face. We then asked the participant about the specific associate the object was last paired with. For example, if the participant responded with "Male" we then presented them with the 4 male faces they were shown throughout encoding and asked them to pick the specific one. Each question was presented on the screen for 3000 ms, however if the participant responded before the 3000 ms and after 1000 ms, they were prompted with the next question. Thus, post-retrieval was semi-self-paced.

2.4.4 Questionnaire

Once participants exited the MRI suite and returned to our lab, they were asked to complete a short questionnaire before the administration of the MoCA. The questionnaire provided information about their approach to the task. The questions aimed to indicate whether participants noticed that some objects were paired with a different associate during encoding and if they utilized any strategies during the encoding phase that may affect their memory accuracy.

2.5 fMRI Analyses

2.5.1 Preprocessing

Scanning was performed on a 3T Siemens TIM Trio system at the Center for Advanced Brain Imaging. Functional data was acquired using a gradient echo pulse sequence (37 transverse slices oriented along the anterior-posterior commissural axis with a 30-degree upward tilt to avoid the eyes, repetition time of 2 s, echo time of 30 ms, 3×3×3.5 mm voxels, 0.8 mm interslice gap). Three encoding and three retrieval blocks of 284 volumes were acquired. The first 2 volumes of each block were discarded to allow for equilibration effects. A high-resolution T1- weighted magnetization-prepared rapid acquisition gradient echo (MPRAGE) image was collected for normalization.

2.5.2 Statistical Analyses

Data were preprocessed and analyzed via SPM12 (SPM12, http://www.fil.ion.ucl.ac.uk/spm/software/spm12/). Images were corrected for differences in slice timing acquisition using the middle slice of each volume as the reference, spatially realigned and resliced with respect to the first volume of the first block. Each participant's MPRAGE scan was coregistered to the mean EPI image, produced from spatial realignment. Each coregistered structural scan was then segmented using the Diffeomorphic Anatomical Registration Through Exponentiated Lie algebra (DARTEL) SPM 12 toolbox (Ashburner, 2007). DARTEL is a suite of tools fully integrated with SPM 12, which the SPM 12 manual recommends over optimized normalization, to achieve sharper nonlinear registration, for intersubject alignment. This method also achieves better localization of fMRI activations in Montreal Neurological Institute [MNI] space. This method has been used successfully in several previous studies with various healthy and neurological populations (Pereira et al., 2010; Yassa & Stark, 2009). Briefly, the gray and white matter segmented images were used to create a study-specific template using the

DARTEL toolbox and the flow fields containing the deformation parameters to this template for each subject were used to normalize each participant's realigned and resliced EPIs to MNI space. Normalized EPI images were written to 3 × 3 × 3 mm and smoothed with an 8 mm full-width at half-maximum isotropic Gaussian kernel. The EPI data was then high-pass filtered to a minimum of 1/128 Hz and grand mean scaled to 100.

2.5.3 Univariate Analyses

Statistical analysis was performed in two stages. First, neural activity was modeled as a series of 0-sec epochs at study (i.e., delta functions) of the various event types (e.g., high interference correct, high interference incorrect) and convolved with a canonical hemodynamic response function. The time courses were then down-sampled to the middle slice to form the covariates for the General Linear Model. For each participant and block, six covariates representing residual movement-related artifacts, determined by the spatial realignment step, were included in the first-level model to capture residual (linear) movement artifacts. Voxel-wise parameter estimates for these covariates were obtained by restricted maximum-likelihood estimation, using a temporal high-pass filter (cutoff 128 sec) to remove low frequency drifts and modeling temporal autocorrelation across scans with an AR(1) process. Contrasts of the parameter estimates for each participant were submitted to the second stage of analysis (treating participants as a random-effect). A mixed ANOVA model was created separately for the encoding and retrieval periods that allowed us to examine both within group effects and group interactions. For each period, a 5 × 2 model included factors of Trial Type (High Interference Correct, High Interference Incorrect, Low Interference Correct, Low Interference Incorrect, No Interference Correct), and Age Group (Young, Old). Correct trials were trials in which the participant correctly

identified the target category at both retrieval and post-retrieval. In order to have enough trials to compare correct to incorrect trials, our incorrect trials were the trials in which the participant incorrectly identified the target category at both retrieval and post-retrieval and the responses in which the participant changed their responses between retrieval and post-retrieval. This was under the premise that if the participant did change their response, they did not have a strong memory trace for that object-associate pairing and were likely guessing. Indeed, behavioral analyses, presented below, show that the change trials were similarly likely to be correct as incorrect, and those that made more change responses had worse associative memory accuracy. Most participants still had low trial counts for the no interference incorrect condition and thus this condition was not included in the analysis. Importantly, this ANOVA model allowed us to not only assess interference effects (i.e. High Interference Correct > Low Interference Correct) using directional t-test comparisons, but also determine whether regions sensitive to interference are also sensitive to accuracy (i.e. High Interference Correct > High Interference Incorrect).

Covariates modeling the mean across conditions for each participant were also added to each model for all contrasts in the second-level model to remove between-subject variance of no interest, as per the optimal event-related fMRI suggestions in chapter 10 of the SPM manual (SMP12; www.fil.ion.ucl.ac.uk/spm/doc/manual.pdf). A weighted least squares estimation procedure was used to correct for inhomogeneity of covariance across within-group conditions and inhomogeneity of variance across groups.

The SPM for the main effects of Trial Type (across groups) and Memory Accuracy (across groups) was masked exclusively with the SPMs for the interactions between these

factors using a liberal uncorrected threshold of $p < .05$ for the masks to restrict memory effects to those "common" (i.e., similar size) across groups/conditions.

First, for regions in which we had a priori hypotheses about, a small volume correction (SVC) was conducted on coordinates of our previous study (Dulas & Duarte, 2016) as well as two anatomical regions. Specifically, we created a sphere with a 10 mm radius around the left-VLPFC [-50, 24, 31], the left-DLPFC [-22, 39, 49], the left-aPFC [-9, 65, 19] and used bilateral hippocampi masks from the AAL atlas. Second, to reveal any unpredicted regions that were sensitive to our effects of interest, we performed multiple comparison correction over the whole-brain. To determine the parameters for multiple comparison corrections, we used FMRISTAT (http://www.math.mcgill.ca/keith/fmri-stat/) to acquire the cluster extent and t-value threshold for voxel-level statistics. All results were thresholded at $p < .001$ with a cluster extent of 17, which yielded whole-brain results corrected for multiple comparisons at $p < .05$. We derived this threshold via Monte Carlo simulations to correct for Type I and Type II errors (Slotnick, Moo, Segal, & Hart, 2003)[1]. Further, all effects were confirmed via inclusive masking ($p < .01$) with each side of the effect (i.e. young and older adult effects) in order to elucidate the source of interactions in a given contrast (e.g. Young > Old: High Interference Correct > High Interference Incorrect), allowing us to determine whether an effect was driven by a group crossover, or whether an effect was in fact larger in one group than another, as well as to ensure that main effects across groups were reliable for each group.

[1] Our XYZ matrix dimensions were 68 × 68 × 37, with a 3 × 3 × 3.5 mm voxel size resampled to 3 × 3 × 3 mm. The Gaussian full-width half-maximum was set to 15, which was the most conservative (highest) value computed using the t-statistic maps associated with the contrasts of interest. 1000 simulations were run.

2.5.4 Multivariate Pattern Analyses

Classification analyses were conducted with two separate classifiers: one targeting the robust sensitivity to perceptual category-level information (faces, scenes) at encoding and one targeting the neural reactivation of category-level information (faces, scenes) at retrieval. Classifier analyses were based on penalized logistic regression using L2-norm regularization, as instantiated in the LIBLINEAR classification library (http://www.csie.ntu.edu.tw/~cjlin/liblinear/). Multi-voxel pattern analysis was performed on the stimulus presentation period, during encoding this was when the participant was presented with the associate-object pair and during retrieval this was when the participant was presented with the object and asked to make the recognition decision. During both encoding and retrieval, classification analyses were performed on the four TRs following stimulus onset, the TRs were weighted as [0 .25 .5 .25]. This weighting scheme was chosen as it generally conforms to the hemodynamic response function and confines classification to data from the currently presented stimulus and not data from the following presented stimulus.

Both classifiers were trained to discriminate between face and scene categories during the fourth encoding block. For the training data, encoding trials were grouped according to the category of the currently encoded image (target), regardless of interference condition. For example, the face category corresponds to encoding trials in the conditions: high interference face target, low interference face target, and no interference face target. For the first classifier, classification analyses were performed by 2-fold cross validation in which one encoding run was left out for testing on each fold while the other two encoding runs were trained on. This was repeated until all three encoding runs were included in both

the training and testing. For the second classifier, classification analyses were performed on independent data sets. The classifier was trained on all three runs of the fourth block of encoding task and tested on all three runs of the retrieval task. For both of these analyses, a penalty parameter of 1 was used. Data preprocessing for classification was performed using the Princeton MVPA Toolbox (http://www.pni.princeton.edu/mvpa/) and custom Matlab scripts.

Both classification analyses were restricted to a bilateral anatomical mask from the AAL atlas that included ventral temporooccipital cortex (VOTC; fusiform gyri, parahippocampi, inferior temporal gyri). This feature selection was chosen for two reasons: 1) these visual association areas have been shown in numerous univariate studies to be differentially sensitive to scene and face stimuli, and 2) the exclusion of voxels not specifically sensitive to these categories helps to improve classification performance. The mask consisted of 1,382 total voxels. For both classification analyses, we employed an additional non-peaking feature selection of choosing the top 500 voxels in the training set. The top 500 voxels were determined by running an ANOVA between the categories in the training set to determine which voxels had the maximal discrimination between categories. 500 was the number of voxels chosen because this amount minimized the number of features while maximizing classifier accuracy during the training and testing of the encoding set, as seen in **Figure 3**.

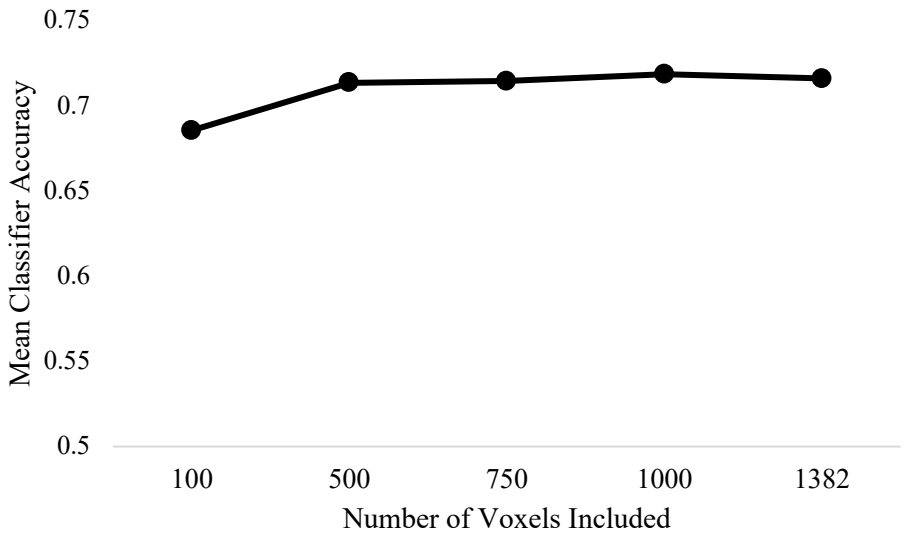

Figure 3 - Mean classification accuracy for all encoding trials as a function of the number of voxels included.

For both classification analyses, the classifier generated a scalar probability estimate that the trial corresponded to a face vs scene. In a logistic regression classifier, the classifier generated a logit value with a range of $+\infty$ to $-\infty$ - this measure can be interpreted as the strength of "evidence" for one category, or how far this test pattern is from the decision-boundary. As this is a binary classification, any value greater than 0 is in favor of category A, in this case a face, and any value less than 0 is in favor of category B, in this case a scene. For each trial in the testing set, the classifier chose the category that had the highest probability estimate (i.e. greater than or less than 0) and was recorded as either correct or incorrect based on whether the classifier's chosen category corresponded to the target category of that trial. At encoding, the target category was what target associate was presented on the screen during that trial. At retrieval, the target category was what category the participant was to retrieve, not what category the participant chose.

Our classification data for both analyses were reported in two ways. First, classification was computed as classification accuracy – the percentage of trials the classifier correctly identified. Second, classification was computed as classifier evidence – the reported probability estimate for the target category. The classifier evidence value was transformed from a logit to a percentage with a range of 0 to 100 for a clearer presentation of target evidence. For both classifier accuracy and evidence, the data was subsampled such that it was reported for each level of interference and memory accuracy.

CHAPTER 3. RESULTS

3.1 Behavioral Results

For all behavioral analyses, significant interactions at an alpha (α) level of 0.05 were followed up with subsidiary ANOVAs an t-tests to determine the source of the effects. Where appropriate, reported p-values were corrected using Huynh-Feldt corrections.

3.1.1 Target Category (General) Memory Accuracy

To assess interference and age differences for the general details of the pairings, we calculated general memory accuracy as the percentage of responses in which the participant correctly identified the target category at both retrieval and post-retrieval (Accuracy = [target category correct response count/all 216 trials]), where chance is equal to 0.25. These percentages are displayed in **Figure 4**.

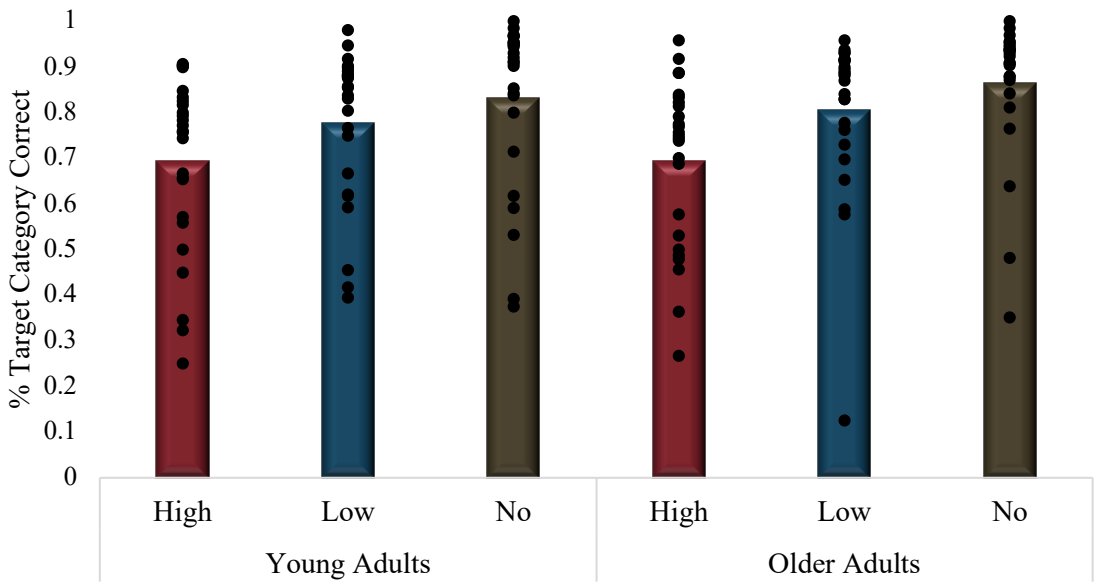

Figure 4 - The mean percentage of correct responses for target category separated by interference condition, for young and older adults. Dots represent individual memory performance.

A 3 Interference (High Interference, Low Interference, No Interference) X 2 Age (Young, Old) ANOVA on these percentages revealed a main effect of Interference [$F(2,96) = 42.229$, $p < .001$, $\eta 2p = .468$], but no main effect of Age [$F(1,48) < 1$, $p = .651$, $\eta 2p = .004$] nor an Interference by Age Interaction [$F(2,96) < 1$ $p = .574$, $\eta 2p = .011$]. As predicted, both young and older adults remembered more no interference than high [$t(49) = 8.332$, $p < .001$] and low interference items [$t(49) = 3.616$, $p = .001$] and more low interference than high interference items [$t(49) = 5.939$, $p < .001$].

3.1.2 Specific Target Associate (Specific) Memory Accuracy

We then wanted to assess interference and age differences for the specific details of the pairings. We did this by calculating the percentage of responses in which the participant correctly chose the specific target associate (i.e. if the object was paired with a

male face and the participant chose face, then male and then the correct male face) (Accuracy = [specific target associate correct response count/ retrieval hits]), with chance equal to 13%. These percentages are displayed in **Figure 5**.

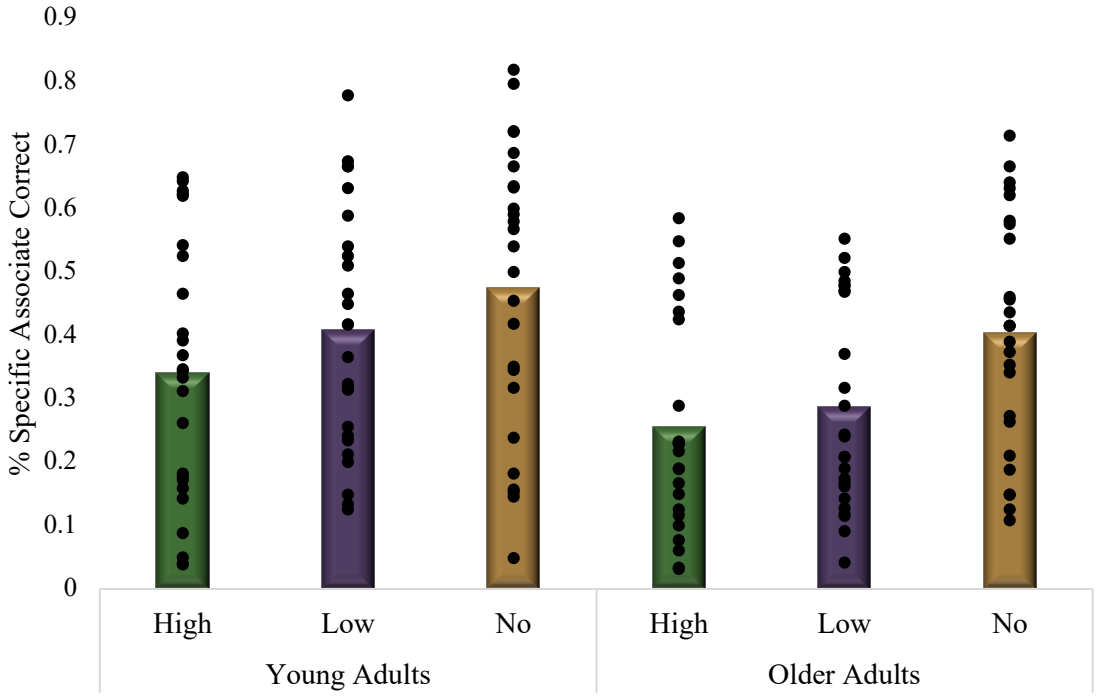

Figure 5 - The mean percentage of correct responses for the specific target associate separated by interference condition, for young and older adults. Dots represent individual memory performance.

A 3 Interference (High Interference, Low Interference, No Interference) X 2 Age (Young, Older) ANOVA on these percentages revealed a revealed a main effect of Interference [$F(2,96) = 47.612$, $p < .001$, $\eta 2p = .498$], a moderate main effect of Age [$F(1,48) = 3.265$, $p = .077$, $\eta 2p = .064$], and no Interference by Age Interaction [$F(2,96) = 1.553$, $p = .217$, $\eta 2p = .031$]. As predicted, both young and older adults remembered more no interference than high [$t(49) = 9.498$, $p < .001$] and low interference items [$t(49) =$

5.551, p < .001] and more low interference than high interference items [t(49) = 3.919, p < .001].

3.1.3 Changed Target Category Responses Between Retrieval and Post-Retrieval

Given that participants were required to make the target category decision at both retrieval and post-retrieval, we were post-hoc interested in how often the participants changed their response and if this differed as a function of interference or age group. We calculated this as [changed response = (different target category response at retrieval and post-retrieval/all responses at retrieval)]. These percentages are presented in **Figure 6**.

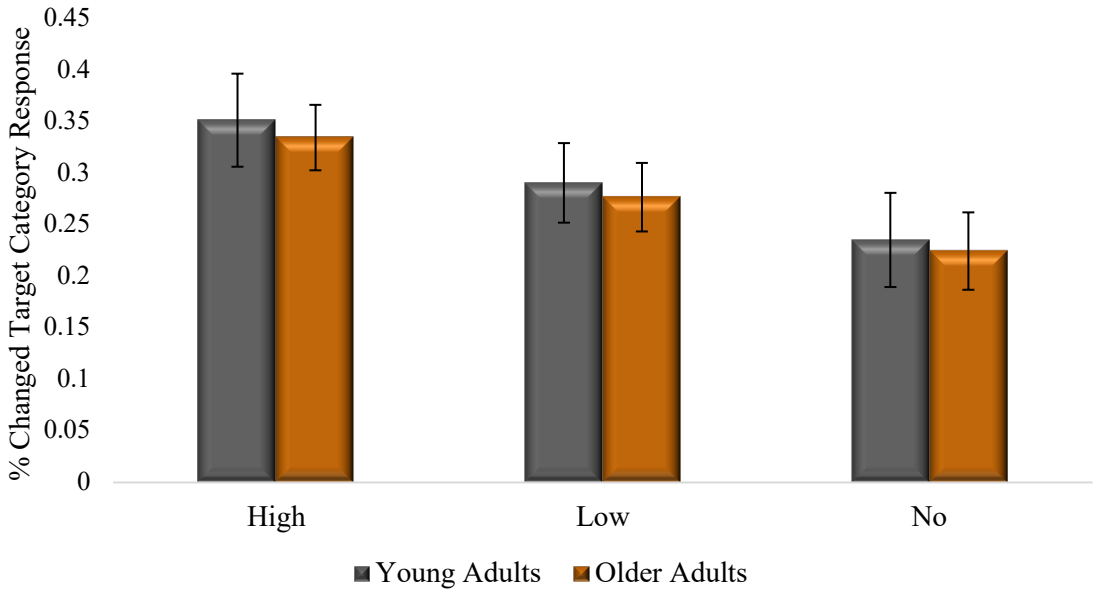

Figure 6 - The mean percentage of changed target category response, regardless of accuracy, between retrieval and post-retrieval separated by interference condition, for young and older adults. Error bars represent the standard error of the mean.

A 3 Interference (High Interference, Low Interference, No Interference) X 2 Age (Young, Older) ANOVA on these percentages revealed a revealed a main effect of Interference [F(2,96) = 29.686, p < .001, η2p = .382], no main effect of Age [F(1,48) < 1,

p = .793, η2p = .001], and no Interference by Age Interaction [F(2,96) < 1, p = .979, η2p = .000]. As predicted, both young and older adults changed their response less for no interference than high [t(49) = 7.561, p < .001] and low interference items [t(49) = 3.980, p < .001] and less for low interference than high interference items [t(49) = 3.932, p < .001].

Given the variability in specific memory performance, presented in **Figure 5**, we investigated if participants who had worse specific memory accuracy were changing their response more often. We evaluated changed responses again, but this time by controlling for their specific memory performance. A 3 Interference (High Interference, Low Interference, No Interference) X 2 Age (Young, Older) ANCOVA on these percentage of changed responses between retrieval and post-retrieval revealed no main effect of Interference [F(2,94) < 1, p = .475, η2p = .016], a moderate main effect of Age [F(1,47) = 3.417, p = .071, η2p = .068], no Interference by Age Interaction [F(2,94) < 1, p = .907, η2p = .002] and an Interference by Specific Memory Interaction [F(2,94) = 3.280, p = .042, η2p = .065]. Overall, young adults changed their responses more than older adults. To determine the direction of the interaction between interference and specific memory, we performed a bivariate correlation between specific memory and the percentage of changed responses for high, low and no interference. This revealed that across age, specific memory accuracy was negatively correlated with high [r(50) = -.506, p < .001], low [r(50) = -.637, p < .001] and no [r(50) = -.649, p < .001] interference suggesting, as seen in **Figure 7**, participants with better memory for specific details of the associate-object pairings changed their responses less than participants with worse memory.

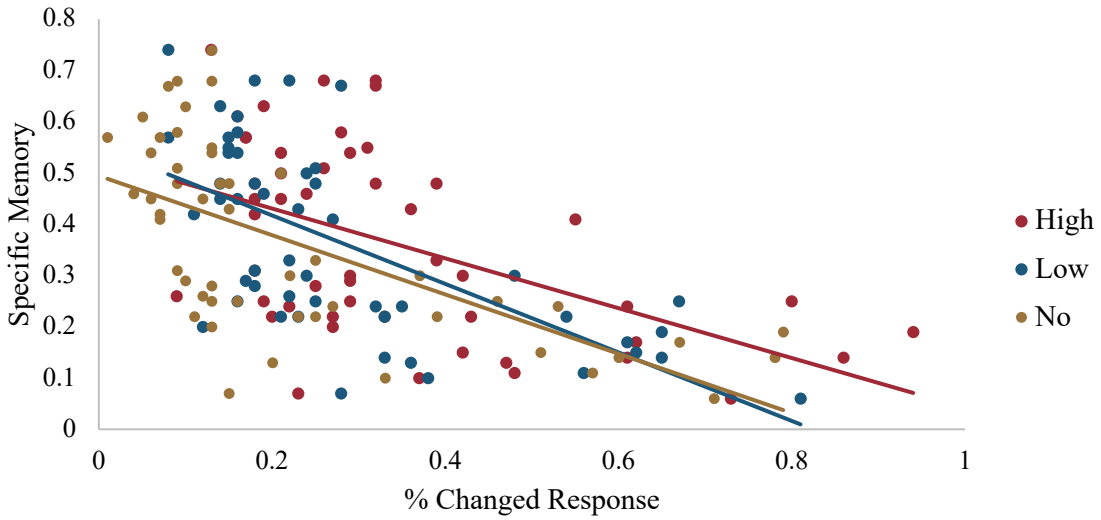

Figure 7 - A scatter plot of mean specific memory accuracy with percent of changed target category response, regardless of accuracy, between retrieval and post-retrieval separated by interference condition.

We then investigated when participants did change their response, how often did they change it to the correct target category. We calculated this as [change to correct = (change to correct target category/all changed responses)]. These percentages are presented in **Figure 8**.

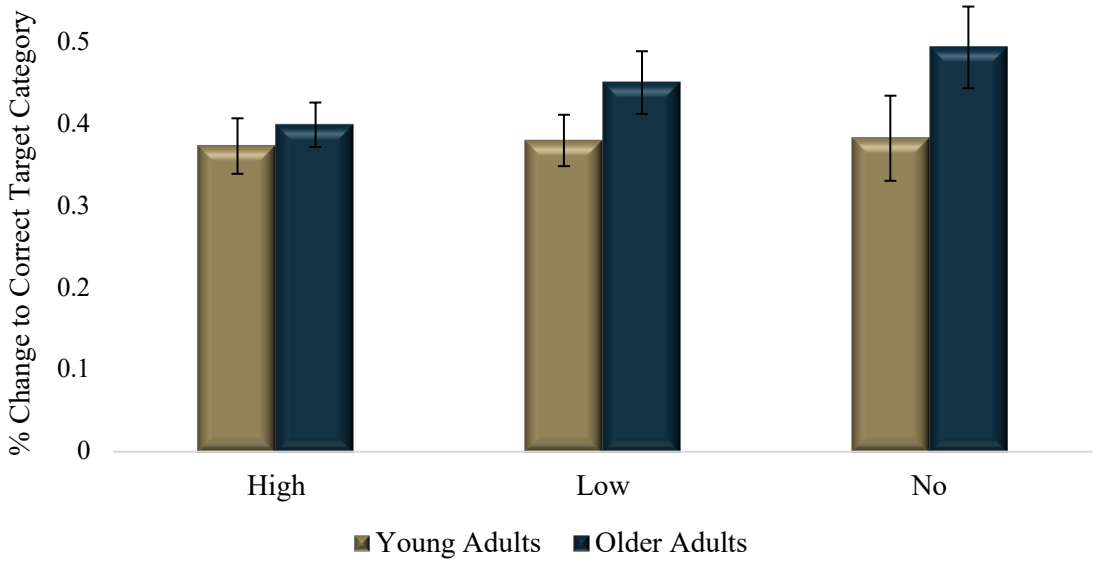

Figure 8 - The mean percentage of changed target category responses to the correct target category between retrieval and post-retrieval separated by interference condition, for young and older adults. Error bars represent the standard error of the mean.

A 3 Interference (High Interference, Low Interference, No Interference) X 2 Age (Young, Older) ANOVA on these percentages revealed a revealed no main effect of Interference [$F(2,96) = 1.097$, $p = .332$, $\eta 2p = .022$], a moderate main effect of Age [$F(1,48) = 3.138$, $p = .083$, $\eta 2p = .061$], and no Interference by Age Interaction [$F(2,96) < 1$, $p = .470$, $\eta 2p = .015$]. Interestingly, older adults were more likely to change their response to the correct than the incorrect target category at post-retrieval, whereas, young adults were equally likely to change their response to the correct or incorrect target category at post-retrieval.

We were also interested in if changing their response to the correct target category benefited specific memory accuracy. We performed a bivariate correlation between their percentage of changed responses to the correct target category and their specific memory

performance. Given the similar relationship between percentage of changed responses and specific memory accuracy across interference above, and for power, we collapsed across interference for this correlation. As seen in **Figure 9**, young adults who had better specific memory were more likely to change their response to the correct target category [r(25) = .405, p = .045], whereas older adults showed no relationship [r(25) = -.065, p = .757].

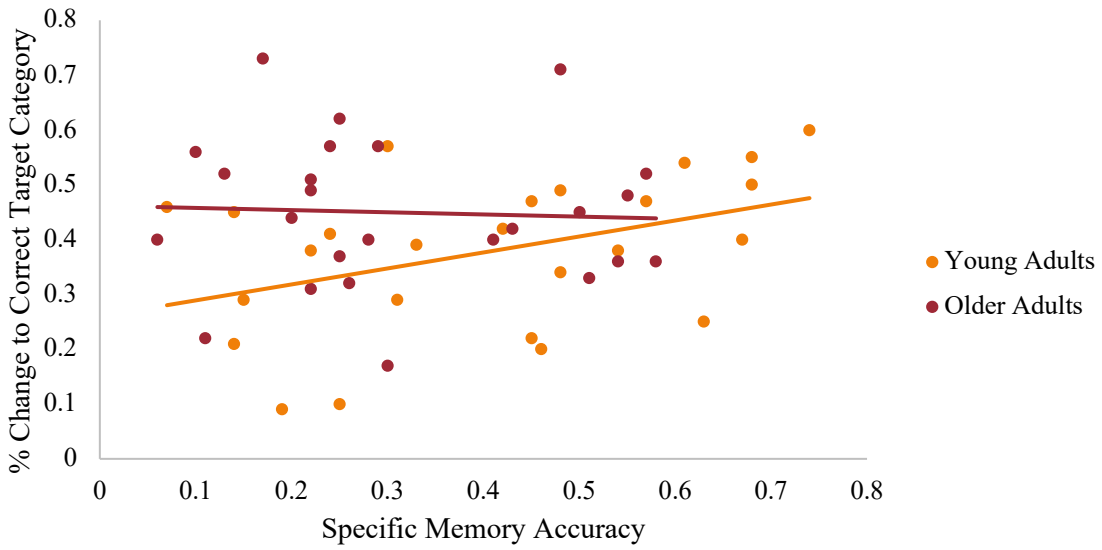

Figure 9 - A scatter plot of mean specific memory accuracy with percent of changed to correct target category response between retrieval and post-retrieval across interference conditions for both young and older adults.

3.1.4 Encoding Reaction Times

We then investigated how reaction times (RTs) differed as a function of interference, subsequent memory performance and age. Equivalent to how we calculated memory performance for general target category memory performance, correct memory performance here was calculated as the percentage of responses in which the participant correctly identified the target category at both retrieval and post-retrieval. Incorrect memory performance was calculated as the percentage of responses in which the

participant incorrectly identified the target category at both retrieval and post-retrieval and the responses in which the participant changed their responses between retrieval and post-retrieval. These two types of trials were grouped to be consistent with our Univariate Analysis in which we needed more trials to investigate incorrect memory performance, as explained in more detail above. As recommended by Faust, Balota, Spieler, and Ferraro (1999), we performed a log transformation on their RTs to account for any age group differences. The log transformation works because it changes any constant proportion to an additive effect, thus allowing us to be confident that any interactions with age are a result of an age-moderated effect and not additive effect. These data are presented in **Figure 10**.

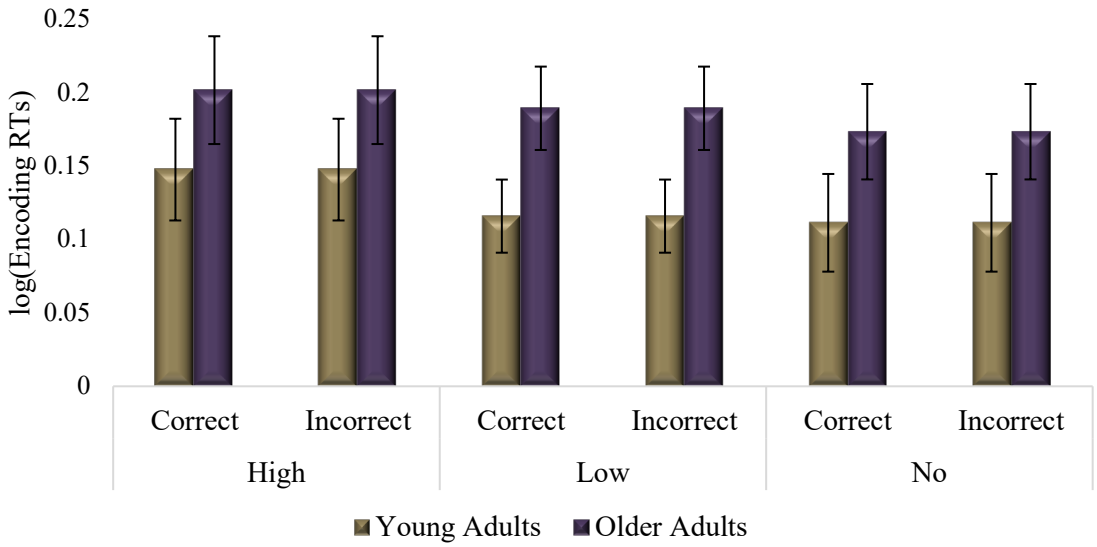

Figure 10 - The mean RT at encoding separated by interference condition and target category memory performance for young and older adults at encoding. Error bars represent the standard error of the mean.

A 3 Interference (High Interference, Low Interference, No Interference) X 2 Memory Accuracy (Correct, Incorrect) x 2 Age (Young, Older) ANOVA on these RTs

revealed a main effect of Interference [$F(2,96) = 6.019$, $p = .004$, $\eta 2p = .111$], a moderate main effect of Memory [$F(1,48) = 3.488$, $p = .068$, $\eta 2p = .068$], a moderate main effect of Age [$F(1,48) = 2.330$, $p = .133$, $\eta 2p = .046$], and no other significant effects [F's $> .002$, p's $< .997$]. Overall, older adults responded slower than young adults and both young and older adults responded slower to incorrect than correct trials. Follow-up t-tests revealed that both young and older adults responded faster to no interference than high [$t(49) = 3.292$, $p = .002$] and low interference items [$t(49) = 2.111$, $p = .040$] and responded similarly to low interference and high interference items [$t(49) = 1.249$, $p = .218$].

3.1.5 Retrieval Reaction Times

We also investigated how RTs differed as a function of interference, target category memory performance and age at retrieval. This analysis was calculated identically to the Encoding RT analysis above. These data are presented in **Figure 11**.

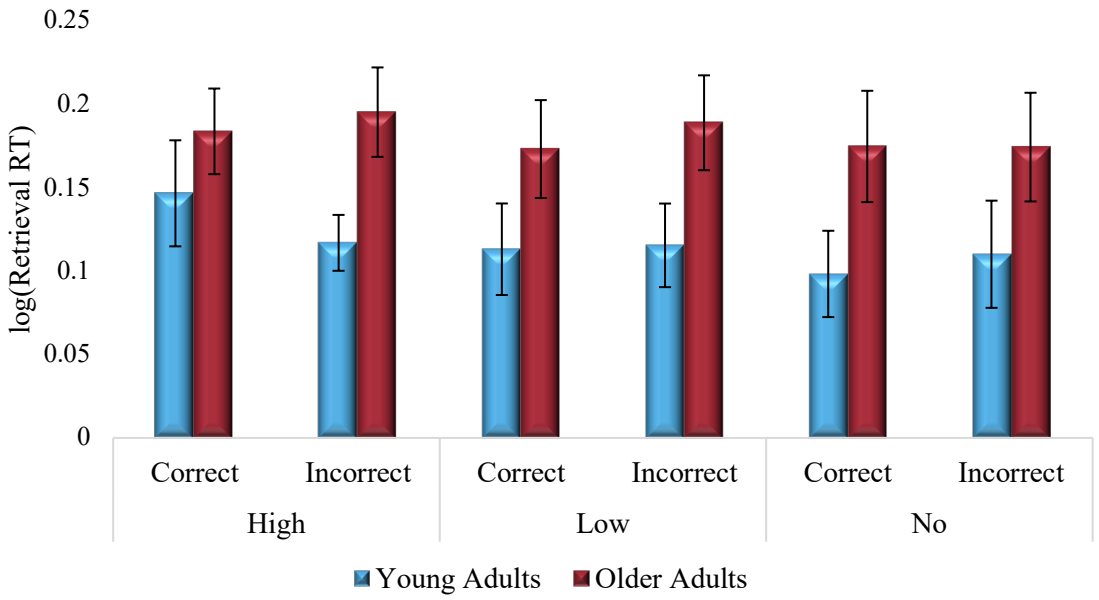

Figure 11 - The mean RT at retrieval separated by interference condition and target category memory performance for young and older adults at retrieval. Error bars represent the standard error of the mean.

A 3 Interference (High Interference, Low Interference, No Interference) X 2 Memory Accuracy (Correct, Incorrect) x 2 Age (Young, Older) ANOVA on these percentages revealed a revealed a main effect of Interference [$F(2,96) = 3.912$, $p = .025$, $\eta 2p = .075$], a moderate main effect of Age [$F(1,48) = 3.025$, $p = .088$, $\eta 2p = .059$], and no other significant effects [F's > .124, p's < .726]. Overall, older adults responded slower than young adults. Follow-up t-tests revealed that both young and older adults responded slower to high interference than no interference [$t(49) = 2.482$, $p = .017$] and low interference items [$t(49) = 2.033$, $p = .047$] and responded similarly to low interference and no interference items [$t(49) = 1.072$, $p = .289$].

3.2 Univariate Results

3.2.1 SVC Analyses

No significant voxels in our ROIs were found to be sensitive to our contrasts of interest at encoding [t's > -.53, p's < 1] nor retrieval [t's > -.67, p's < 1].

3.2.2 Whole-Brain Analyses

We first sought to determine what regions in the brain were sensitive to the level of interference regardless of accuracy and which regions were sensitive to the successful resolution of interference, to do this we conducted a whole-brain analyses.

3.2.2.1 Encoding

Consistent with our hypothesis, the more caudal PFC, specifically the VLPFC, as seen in **Figure 12**, showed greater effects for high interference trials than no interference trials and high/low interference trials than no interference trials. No regions showed significant interactions between age and interference level. No regions showed greater effects for correct trials incorrect trials nor significant interactions between age, interference level and accuracy. The regions for each contrast are presented in **Table 2**.

Table 2 - Peak coordinates for whole-brain analysis of the Encoding Task

Region	*L/R*	*BA*	*x, y, z*	*t-score*	*Cluster size*
Across Age: High > No					
Fusiform Gyrus	L	37	-48, -55, -10	3.97	24
Ventrolateral PFC	L	45/47	-33, 35, -13	4.13	19
Across Age: High/Low > No					
Ventrolateral PFC	L	47	-39, 44, -13	3.76	25
Ventrolateral PFC	R	47	36, 38, -10	4.12	21

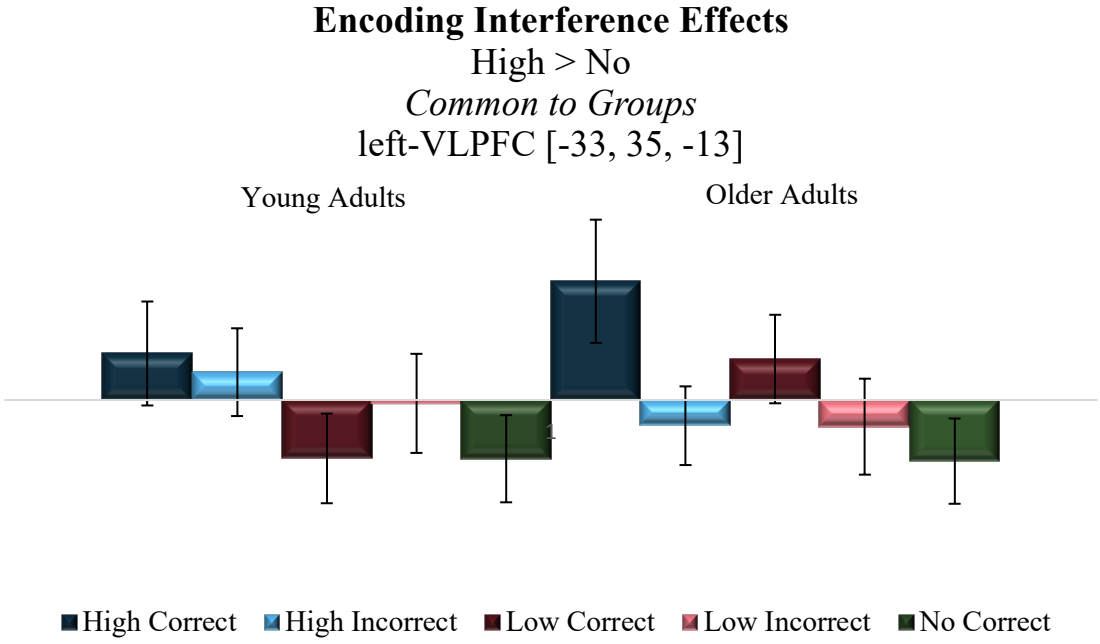

Figure 12 - Interference effects at encoding for the left-VLPFC ROI. Plots show parameter estimates for high interference correct and incorrect trials, low interference correct and incorrect trials and no interference correct trials. Error bars represent the 90% confidence interval. Exclusive masking conducted as described in the fMRI analysis section.

3.2.2.2 Retrieval

Several regions showed greater effects for high/low interference correct trials than high/low interference incorrect trials. Inconsistent with our hypothesis, the DLPFC did not seem to be sensitive to this effect of interest, however the vmPFC was, as seen in **Figure 13**. No regions showed significant interactions between age and interference level. Additionally, no regions showed greater effects for high interference than no interference trials, nor significant interactions between age, interference level and accuracy. These regions are presented in **Table 3**. Even at a substantially reduced threshold of p = .005, there were no significant voxels in the left-VLPFC that were sensitive to interference but

not accuracy, nor any significant voxels in the DLPFC or hippocampus that were sensitive to accuracy.

Table 3 - Peak coordinates for whole-brain analysis of the Retrieval Task

Region	*L/R*	*BA*	*x, y, z*	*t-score*	*Cluster size*
Across Age: High/Low Correct > High/Low Incorrect					
Ventromedial PFC	R	11	6, 23, -7	4.36	212
Supramarginal Gyrus	L	40	-66, -34, 23	3.72	26
Secondary Visual Cortex	L	18	-12, -91, -10	3.83	25

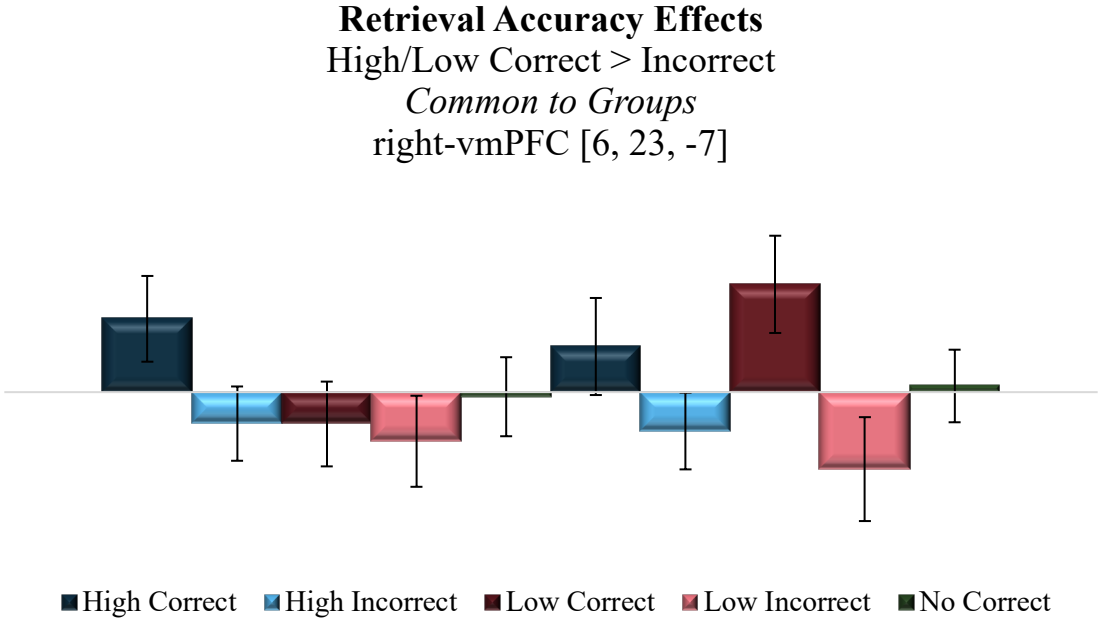

Figure 13 - Accuracy effects at retrieval for the right-vmPFC ROI. Plots show parameter estimates for high interference correct and incorrect trials, low interference correct and incorrect trials and no interference correct trials. Error bars represent the 90% confidence interval. Exclusive masking conducted as described in the fMRI analysis section.

In **Figure 13**, it appears as though young adults show no difference in vmPFC activity between correct and incorrect low interference trials, whereas older adults show a

difference. To determine if there was an Interference by Memory by Age interaction, we extracted mean activity from this vmPFC coordinate and put it into a 2 Interference (High Interference, Low Interference) X 2 Memory Accuracy (Correct, Incorrect) x 2 Age (Young, Older) ANOVA. We only included High and Low Interference in this ANOVA because there were not enough No Interference incorrect trials to include. This ANOVA revealed a main effect of Memory [$F(1,48) = 19.941$, $p < .001$, $\eta 2p = .289$], an Interference by Age interaction [$F(1,48) = 3.748$, $p = .059$, $\eta 2p = .072$], an Interference by Memory by Age interaction [$F(1,48) = 6.515$, $p = .014$, $\eta 2p = .120$] and no other significant effects [F's $> .030$, p's $< .864$]. Consistent with our analysis above, both young and older adults recruited the vmPFC more for high/low correct than high/low incorrect trials. Follow-up age specific ANOVAs revealed a moderate Interference by Memory interaction in young adults [$F(1,24) = 3.184$, $p = .087$, $\eta 2p = .117$] and older adults [$F(1,24) = 3.343$, $p = .080$, $\eta 2p = .122$]. Young adults recruited the vmPFC more for high interference correct than incorrect trials [$t(24) = 2.858$, $p = .009$], but similarly recruited the vmPFC for low interference correct and incorrect trials [$t(24) = .420$, $p = .678$]. Older adults recruited the vmPFC more for high interference correct than incorrect trials [$t(24) = 2.117$, $p = .045$] and more for low interference correct than incorrect trials [$t(24) = 4.123$, $p < .001$].

3.3 Multivariate Pattern Results

We sought to examine the underlying processes of proactive interference, specifically if old associations (lures) were reliably reactivated during attempts to recover recent ones (targets) in both age groups and if the relative amount of target vs. lure reactivation differed as a function of mnemonic interference and age. We investigated this

in both encoding and retrieval and for both general target memory and specific target associate memory.

3.3.1 Perceptual Category-Level Information Classifier

Classification analyses were performed on the encoding task by training and testing on the fourth block of encoding using the leave-one-out method. The classifier was trained to discriminate between faces and scenes (i.e. targets and lures) in the VOTC. Trial-by-trial classifier accuracy was significantly greater than chance (mean = 71.39%, [$t(49) = 14.387$, $p < .001$]), confirming robust sensitivity to perceptual category-level information (faces, scenes) at encoding.

Once we confirmed that the classifier was sensitive to category-level information, we then subsampled the data based on interference condition and subsequent general target category memory accuracy. To be consistent with our univariate analyses, general target category memory accuracy was calculated as the percentage of responses in which the participant correctly identified the target category at both retrieval and post-retrieval. Incorrect memory performance was calculated as the percentage of responses in which the participant incorrectly identified the target category at both retrieval and post-retrieval and the responses in which the participant changed their responses between retrieval and post-retrieval.

3.3.1.1 Classifier Accuracy

We first ran a 3 Interference (High Interference, Low Interference, No Interference) X 2 Age (Young, Older) ANOVA on classifier accuracy for memory correct trials to

investigate how classifier accuracy differed as a function of interference and age. We did not include memory as a factor in this ANOVA because we did not have a sufficient number of no interference incorrect trials. This ANOVA revealed no significant effects or interactions [F's > .004, p's < .948]. We then ran a 2 Interference (High Interference, Low Interference) X 2 Memory (Correct, Incorrect) X 2 Age (Young, Older) ANOVA on classifier accuracy to investigate how classifier accuracy differed as a function of interference, subsequent memory performance and age. This ANOVA revealed an interference by memory interaction [$F(1,48) = 4.829$, $p = .033$, $\eta 2p = .091$] and no other significant effects [F's > .043, p's < .837]. Follow-up paired t-tests revealed that both young and older adults subsequently remembered the general target category, their classifier accuracy was greater than when they subsequently forgot the general target category under conditions of high interference [$t(49) = 2.220$, $p = .031$] but not low interference [$t(49) = .769$, $p = .446$]. These data are presented in **Figure 14**.

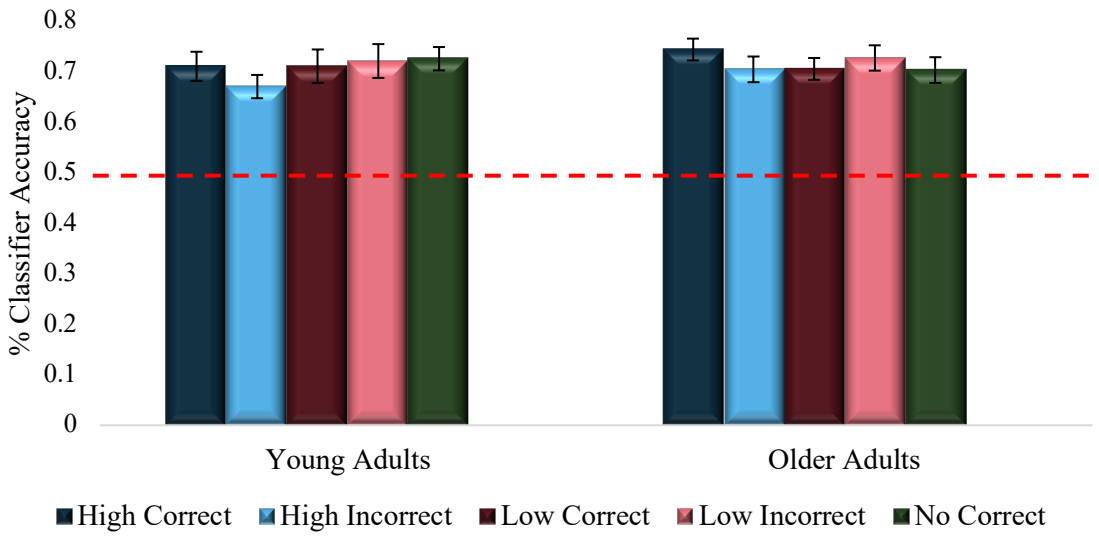

Figure 14 - Classifier accuracy for the perceptual category-level information classifier at encoding as a function of interference, subsequent general category memory performance and age.

3.3.1.2 Classifier Evidence

We also examined classifier evidence - the reported probability estimate for the target category. For presentation purposes, the classifier evidence value was transformed from a logit to a percentage with a range of 0 to 100. We were interested in if the relative amount of target vs lure evidence differed as a function of interference, subsequent memory performance or age, thus we again subsampled the data.

Parallel to our analysis on classifier accuracy, we first ran a 3 Interference (High Interference, Low Interference, No Interference) X 2 Age (Young, Older) ANOVA on classifier evidence for memory correct trials to investigate how classifier evidence differed as a function of interference and age. This ANOVA revealed no significant effects or interactions [F's > .200, p's < .819]. We then ran a 2 Interference (High Interference, Low Interference) X 2 Memory (Correct, Incorrect) X 2 Age (Young,

Older) ANOVA on classifier evidence to investigate how classifier evidence differed as a function of interference, subsequent memory performance and age. This ANOVA revealed no significant effects or interactions [F's > .036, p's < .850]. These data are presented in Table 6.

Table 4 - Mean target evidence for the perceptual category-level information classifier separated by Interference, subsequent general target category memory performance and age.

	High		Low		No
	Correct	Incorrect	Correct	Incorrect	Correct
Young Adults	87.7(12.9)	87.1(9.1)	87.5(12.1)	88.0(12.3)	88.1(10.7)
Older Adults	88.5(5.1)	89.5(4.5)	88.7(3.8)	86.9(5.8)	89.7(3.1)

3.3.2 Neural Reactivation of Category-Level Information Classifier

Classification analyses were performed on the retrieval task by training on the fourth block of encoding and testing on retrieval. The classifier was trained to discriminate between faces and scenes (i.e. targets and lures) in the VOTC. Trial-by-trial classifier accuracy was not significantly greater than chance (mean = 50.79%, [t(49) = 1.101, p = .276]), as seen in **Figure 15**, suggesting that the classifier cannot decode the neural reactivation of category-level information (faces, scenes) at retrieval. Unfortunately, because classifier accuracy is not different from chance, we are not able to interpret these results.

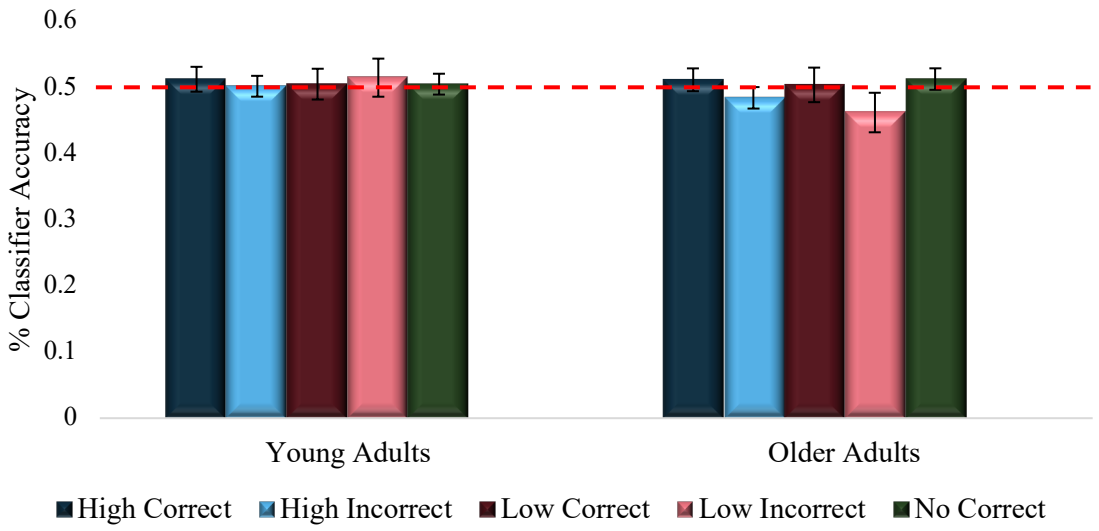

Figure 15 - Classifier accuracy for the neural reactivation of category level information classifier at retrieval as a function of interference, subsequent memory performance and age.

CHAPTER 4. DISCUSSION

As previously discussed, the "frontal aging hypothesis" fails to discern between the various PFC subregions and the processes they support that underlie age-related cognitive declines. The current study investigated the roles the VLPFC and DLPFC play in age-related impairments in associative memory and additionally the neural mechanisms behind overcoming interference in memory. As predicted, the left-VLPFC was sensitive to the level of interference, but not the successful resolution of interference for both young and older adults at encoding. Interestingly, the vmPFC, but not the DLPFC was not sensitive to the successful resolution of interference at retrieval. Young adults recruited the vmPFC more during correct than incorrect high interference trials but not more during correct than incorrect low interference trials. Older adults on the other hand, recruited the vmPFC more for correct than incorrect for both high and low interference trials. These results and their implications are discussed below.

4.1 Behavioral Results

Consistent with previous studies (Burton et al., 2019; Dulas & Duarte, 2016; Ebert & Anderson, 2009; Guez & Naveh-Benjamin, 2016; Jacoby et al., 2005), both young and older adults were susceptible to proactive interference in associative memory, as evidenced by interference effects in memory accuracy and RTs. Associative memory accuracy for the general target category worsened as the level of interference increased. This suggests that when interference from the lure associate is high, the ability to successfully retrieve, even general details about the target associate is impaired. As we predicted, this was the case for both young and older adults. We predicted that as this type of memory was due to

familiarity, rather than recollection, older adults would be able to perform equally as well as young adults, as has been found in previous studies (for review, Yonelinas, 2002). Additionally, our encoding task was very engaging and likely provided older adults with an effective encoding strategy which benefited their associative memory accuracy. Our task was an interactive imagery task that required participants to imagine the images interacting and then rate how easy or hard to was to do so. Previous studies have found that age-related associative memory deficits are reduced when older adults are given effective encoding strategies that they typically fail to self-initiate in less engaging tasks (Glisky & Kong, 2008; Glisky, Rubin, & Davidson, 2001; Hay & Jacoby, 1999; Naveh-Benjamin, Brav, & Levy, 2007).

Associative memory accuracy for the specific target associate also worsened as the level of interference increased. This again suggests that when interference from the lure associate is high, the ability to successfully retrieve specific details about the target associate is impaired. There was a marginal main effect of age, in which young adults had marginally better memory accuracy for the specific target associate than older adults, but there was no age by interference interaction. We predicted that older adults would have disproportionately worse memory performance for the specific high interference trials. The lack of this finding in the current study could again be attributed to our engaging encoding task which provided older adults with an effective encoding strategy that could have improved their performance not only for the general target category, but for the specific target associate also.

Consistent with previous studies, RTs at both encoding and retrieval were slower as the level of interference increased (for review, Jonides & Nee, 2006). At encoding, both

young and older adults responded faster to no interference items than high and low interference items, but did not respond differently to high and low interference items. This suggests that they were sensitive to interference and perhaps were engaging in more effortful encoding of the target-object pair, as these objects had previously been paired with lures. At retrieval, both young and older adults responded slower to high interference items than no and low interference items but did not respond differently to low and no interference items. This suggests that young and older adults may have had a more difficult time resolving interference under high conditions than low, likely due to the number of times the target associate was paired with the object during encoding. Such that, participants had an easier time successfully resolving low interference items because they had only seen it paired with the lure once, compared to high interference items in which the object was paired with the lure twice.

Evidence for susceptibility to proactive interference is further corroborated by our finding of an effect of interference on the number of changed responses between retrieval and post-retrieval. Across age, participants changed their target category responses more as the level of interference increased. This effect was driven by participants with worse memory for the specific target associate. After we controlled for memory accuracy for the specific target associate, individuals with worse specific memory accuracy were more likely to change their response than those with better specific memory accuracy. This relationship was stronger for low and no interference items than high interference items suggesting that successfully resolving high interference items was difficult for everyone, even those with stronger memory for details about the target-object pairing. Interestingly, when participants did change their responses, young adults with better specific memory

accuracy were more likely to change their response to the correct target category than young adults with worse specific memory accuracy. Older adults, on the other hand, showed no relationship between specific memory accuracy and changing their response to the correct target category. This suggests that young adults are potentially updating their memory for that target-object pairing after making that first target category response at retrieval, which later benefits their memory for the specific details of the pairing. Whereas, older adults are not updating their memory for the target-object pairing in a way that benefits their memory performance.

In combination with our finding of a marginal age effect in specific memory accuracy, it seems that older adults may be having greater difficulty with this task but are not disproportionately susceptible to interference. This is in line with previous studies (Dulas & Duarte, 2016; Guez & Naveh-Benjamin, 2016), but stands in contrast to others that have found older adults are disproportionately susceptible to proactive interference in associative memory (Burton et al., 2019; Ebert & Anderson, 2009; Jacoby et al., 2005). These mixed results could be attributed to few different possibilities. One possibility is that older adults were able to successfully overcome proactive interference in the current study due to our engaging encoding task. As discussed above, previous studies have found that age-related associative memory deficits are reduced when older adults are given effective encoding strategies that they typically fail to self-initiate in less engaging tasks (Glisky & Kong, 2008; Glisky et al., 2001; Hay & Jacoby, 1999; Naveh-Benjamin et al., 2007). The studies that did find that older adults were disproportionally susceptible to proactive interference just had participants learn word pairs with no environmental support whereas

our study provided older adults with an interactive imagery task that may have benefited their ability to successfully resolve the proactive interference.

A non-mutually exclusive possibility is that these mixed results are due to the sample of young and older adults used in each study. It is possible that some older adults are able to engage in the cognitive control processes necessary to resolve proactive interference to the same level that young adults do. The older adults in the current study were high performing, with minimal medical issues and had, on average, at least a bachelor's degree in education. The previous studies that found that older adults were disproportionately susceptible to proactive interference had older adult samples similar to ours in age range and years of education, however, these studies were not fMRI studies, which likely lessened their sampling bias (Burton et al., 2019; Ebert & Anderson, 2009; Jacoby et al., 2005). Age-related sampling biases are an unfortunate consequence of the way older adults are studied. Health problems and functional limitations (i.e. being able to get themselves to a research lab, being able to use a computer, access to research study advertisements) leads researchers to typically study the "healthiest" of older adults that do not often represent the general population of the elderly. These limitations are exacerbated in fMRI studies in which a number of common health conditions such as high blood pressure, diabetes, history of heart attack and strokes, make participants ineligible. Given the extensive research on the negative impact health-related issues have on cognition (for review, Stern PC, Carstensen LL, & editors, 2000), it is conceivable that older adults who participate in fMRI studies generally have less cognitive difficulties than those who are ineligible to participate. Thus, this discrepancy in older adults' susceptibility to proactive interference may be attributed to the sample of older adults, in which due to our selection

criteria, ours were more high performing and more able to engage in the cognitive control processes necessary to overcome proactive interference. Though this age-related sampling bias is often discussed, to the best of my knowledge, no research has been conducted comparing the cognitive abilities of older adults eligible for fMRI studies with those who are ineligible. Future aging research should focus on this potential limitation and determine the extent these sampling biases have on cognition.

4.2 Univariate Analysis Results

Consistent with previous studies, the left-VLPFC was sensitive to the level of interference but not accuracy (Atkins, Berman, Reuter-Lorenz, Lewis, & Jonides, 2011; Oztekin, Curtis, & McElree, 2009). Such that for both young and older adults, the left-VLPFC was recruited more during high and low interference trials than no interference trials at encoding. The left-VLPFC has been implicated in post-retrieval selection (Badre, Poldrack, Pare-Blagoev, Insler, & Wagner, 2005; Badre & Wagner, 2007; Barredo, Oztekin, & Badre, 2015; Dobbins, Rice, Wagner, & Schacter, 2003; Oren et al., 2017), a process that is engaged when multiple competing representations are activated and relevant information needs to be enhanced while irrelevant information needs to be suppressed. Consistent with our finding that our sample of older adults are not disproportionally susceptible to proactive interference, we did not find an age-related difference in the recruitment of the left-VLPFC, suggesting that older adults may be able to engage in left-VLPFC mediated post-retrieval selection to the same extent as young adults. That is, in the current proactive interference paradigm, older adults may be able to enhance the target and suppress the lure just as well as young adults.

The left-VLPFC being sensitive to interference at encoding suggests that both young and older adults are spontaneously engaging in post-retrieval selection at encoding without being prompted to do so (Kuhl, Bainbridge, & Chun, 2012). Participants may be reactivating the lure associate, while being presented with the target associate in such a way as to suppress that irrelevant lure-object pairing and update their memory with the relevant target-object pairing. Though older adults are typically found to not engage in cognitive control processes unless prompted to do so (Craik, 1986), this data demonstrates that these older adults are spontaneously engaging in post-retrieval selection to resolve interference and to the same extent as young adults.

Interestingly, we found the vmPFC to be sensitive to memory accuracy at retrieval for both young and older adults. Such that the vmPFC was recruited more during high/low interference correct target category trials than high/low interference incorrect target category trials. The vmPFC has been indicated in the monitoring of internally-generated, imagined, information, whereas the lateral PFC is indicated in the monitoring of perceptually-driven information (for review, Mitchell & Johnson, 2009). In the current study, this vmPFC activity likely indicates the monitoring of the successful retrieval of the target-object associative context the participants self-generated at encoding. Thus, it seems that when participants correctly identify the target category, they engage in monitoring of this self-generated associative context more than when they incorrectly identify the target category. For young adults, the vmPFC was recruited more for correct than incorrect high interference trials but not more for correct than incorrect low interference trials. Whereas, for older adults, the vmPFC was recruited more for correct than incorrect for both high and low interference trials. Given the lack of any behavioral age differences in low interference

memory performance, the difference in vmPFC activity for low interference correct and incorrect trials for older adults but not young likely represents a compensatory process. Perhaps young adults were able to successfully retrieve the target-object associative contexts under conditions of low interference without any monitoring. Whereas, older adults needed to monitor their retrieval of this self-generated associative context to successfully retrieve it and match young adults' memory performance. This is in line with the CRUNCH model which posits that older adults recruit cognitive control regions more than young adults to compensate for cognitive decline (P.A. Reuter-Lorenz & Cappell, 2008; P. A. Reuter-Lorenz & Lustig, 2005). CRUNCH additionally proposes that older adults reach their task capacity sooner than young adults so this over recruitment of cognitive control regions but matched performance is typically seen at lower load levels. Consistent with this, older adults recruited the vmPFC more than young adults during low interference correct trials to successfully resolve low interference but similarly recruited the vmPFC during high interference correct trials suggesting that successfully resolving high interference is equally difficult for both young and older adults.

Inconsistent with our previous study (Dulas & Duarte, 2016) and other studies (for review, Badre & Wagner, 2007) the left-VLPFC was not sensitive to interference at retrieval. One possibility for this inconsistency is that since both young and older adults engaged in post-retrieval selection at encoding, they did not need to do so again at retrieval. Perhaps engaging in this process at encoding was sufficient enough to support the subsequent successful resolution of interference. Unfortunately, imaging data was not collected at encoding for these other studies and thus we cannot determine if post-retrieval

selection only needs to be engaged once, at either encoding or retrieval or if it is a process may need to be engaged at both depending on task demands.

If the engagement of post-retrieval selection is a factor of task demands, it is possible that our retrieval task may have lessened these demands. Potentially, not presenting the participant with target and lure stimuli, as previous studies have done, and instead just presenting them with the category labels, may have reduced the demand on post-retrieval selection. As mentioned above, the lateral PFC has been found to be more involved in processes regarding perceptual-driven activity whereas the medial PFC has been found to be more involved in processes regarding self-generated activity (for review, Mitchell & Johnson, 2009). In these previous studies, participants likely recruited left-VLPFC post-retrieval selection to inhibit the lure and enhance the target because they were presented with target and lure stimuli. Whereas, in the current study, participants were not presented with any images of the target and lure that they had to enhance and/or suppress and instead had to successfully retrieve the target-object associative contexts they created at encoding. Similarly, we may not have found any recruitment of the DLPFC because our retrieval task had less of a demand on perception and more of a demand on self-generation than these previous tasks. If this is the case, then it is unsurprising that we did not see any DLPFC post-retrieval monitoring and instead saw vmPFC self-generated monitoring. Participants did not have perceptually driven target and lure images that they had to evaluate but instead had to monitor their retrieval of the target-object associative context.

4.3 Multivariate Pattern Analysis Results

One goal of the current study was to utilize MVPA to examine if old associations (lures) were reliably reactivated during attempts to recover recent ones (targets) in both age groups and if the relative amount of target vs. lure reactivation differed as a function of mnemonic interference, memory performance and age. We examined this at both encoding and retrieval. At encoding we were able to successfully decode perceptual category-level information and found that across age, there was no difference in classifier accuracy across interference. Classifier accuracy did differ as a function of subsequent memory performance but for high interference trials only. This is inconsistent with our hypotheses, in which we predicted that, across age, classifier accuracy would increase as the level of interference decreased and would be less when the incorrectly identified the target category than when they correctly did. This decrease in classifier accuracy would be a function of how much the participants were reactivating the lure, which we predicted they would be doing more during higher interference trials. We then expected that by calculating classifier evidence, and thus calculating the relative amount of target vs lure reactivation for each trial, we would be able to determine that lower classifier accuracy for those higher interference trials was due to participants reactivating the lure to a greater extent than during lower interference trials.

Unfortunately, we also did not find that the relative amount of target vs lure reactivation differed as a function of interference nor subsequent memory accuracy. This was again unexpected given similar studies that have found differences in the amount of target reactivation across conditions (Kuhl et al., 2012; Kuhl, Rissman, Chun, & Wagner, 2011; Thakral, Wang, & Rugg, 2017). We believe that these unexpected findings are a result of how we trained our classifier. We trained it to decode faces vs scenes on the fourth

block of encoding across all trials, regardless of interference. Due to this, we were training on trials in which the participants had already seen the object paired with the lure and as evidenced above in our behavioral and univariate results, were seemingly inhibiting the lure. In other words, while they were viewing the target associate on the screen during these training trials, they were also likely bringing to mind the lure associate to inhibit it. Thus, the classifier learned a pattern of activity for face (target) trials that also involved some level of activity for scene (lure) trials. When the classifier was later tested on trials in which the participant could have again been reactivating the lure, the classifier was not sensitive to any lure reactivation because it had been trained on it and thus target and lure evidence did not differ across our conditions. Unfortunately, due to low trial counts we had to train on trials across all levels of interference. If we would have been able to train just on no interference trials, where the participants were only focusing on the target presented and not reactivating a lure, we likely would have seen differences in target and lure evidence across interference. Given this and how unexpected our results turned out, it seems best to not put too much credence into this analysis. Therefore, we will not interpret the encoding classifier results.

We were also not able to successfully decode neural reactivation of the target and lure at retrieval. This was again unexpected, as previous studies with similar tasks were able to train on their encoding data and successfully test on their retrieval data within the VOTC (Kuhl et al., 2012; Kuhl et al., 2011). This cannot be completely attributed to MVPA methods, as we all used penalized logistic regression with L2-norm regularization, all performed classification in the VOTC and generated our masks from the AAL atlas. The most likely reasoning behind this is the task itself, in which what we trained and tested the

classifier on was quite different from what these other studies trained and tested their classifier on. Both Kuhl et al. (2011) and (Kuhl et al., 2012), instructed participants to remember word-image pairs during encoding. At retrieval, they presented participants with a word above an empty box and had them respond with either the category of the image they were supposed to retrieve or "don't know". Though our task is similar, it differs in quite a few ways. For one, we had participants encode image-image pairs, whereas these studies had participants encode word-image pairs. Additionally, our task required participants to engage in much more interactive imagery. Participants were required to imagine the object-associate images together in the real world and then rate how hard it was to do. This is a fundamentally different task than asking participants to remember a word-image pair. Potentially at retrieval, participants in these other studies retrieved the word-image pair in a similar way to how they encoded it. Whereas, in our task, the process participants used to retrieve the object-associative image pair may have been completely different from the process they used at encoding to imagine the images together in the real world. Unfortunately, to the best of my knowledge, the similarity between interactive imagery encoding neural processes and retrieval neural processes has never been investigated. Thus, though it is probable that stimulus modality and the type of encoding strategy utilized has some effect on the ability to successfully decode neural reactivation at retrieval, the magnitude of these effects remains unclear. MVPA is a relatively new analysis and there is still much the field does not understand about it. As more research is conducted on how these seemingly minor task differences affect classifier performance, we will begin to have a clearer understanding on why some classifier analyses are successful and some unsuccessful.

4.4 Conclusion

The present study adds to the growing body of literature suggesting that older adults are not disproportionally susceptible to proactive interference in associative memory tasks. Older adults recruited the right-vmPFC more than young adults during the successful resolution of low interference but not high interference. Consistent with the CRUNCH model, at lower task demands, older adults had to engage in more monitoring of their successful retrieval of the associative pairings to perform at the same memory performance level as young adults. However, at higher levels of interference, young and older adults had to engage in a similar amount of monitoring to successfully resolve interference. Additionally, older adults were able to spontaneously engage in left-VLPFC post-retrieval selection to the same extent as young adults. Collectively, these results suggest that some older adults are able to engage in the cognitive control processes necessary to resolve proactive interference to the same extent as young adults.

REFERENCES

Achim, A. M., & Lepage, M. (2005). Dorsolateral prefrontal cortex involvement in memory post-retrieval monitoring revealed in both item and associative recognition tests. *Neuroimage, 24*(4), 1113-1121. doi:10.1016/j.neuroimage.2004.10.036

Angel, L., Bastin, C., Genon, S., Balteau, E., Phillips, C., Luxen, A., . . . Collette, F. (2013). Differential effects of aging on the neural correlates of recollection and familiarity. *Cortex; a journal devoted to the study of the nervous system and behavior, 49*(6), 1585-1597. doi:10.1016/j.cortex.2012.10.002

Ashburner, J. (2007). A fast diffeomorphic image registration algorithm. *Neuroimage, 38*(1), 95-113. doi:S1053-8119(07)00584-8 [pii] 10.1016/j.neuroimage.2007.07.007

Atkins, A. S., Berman, M. G., Reuter-Lorenz, P. A., Lewis, R. L., & Jonides, J. (2011). Resolving semantic and proactive interference in memory over the short-term. *Mem Cognit, 39*(5), 806-817. doi:10.3758/s13421-011-0072-5

Atkins, A. S., & Reuter-Lorenz, P. A. (2011). Neural mechanisms of semantic interference and false recognition in short-term memory. *Neuroimage, 56*(3), 1726-1734. doi:10.1016/j.neuroimage.2011.02.048

Badre, D. (2008). Cognitive control, hierarchy, and the rostro-caudal organization of the frontal lobes. *Trends Cogn Sci, 12*(5), 193-200. doi:10.1016/j.tics.2008.02.004

Badre, D., Poldrack, R. A., Pare-Blagoev, E. J., Insler, R. Z., & Wagner, A. D. (2005). Dissociable controlled retrieval and generalized selection mechanisms in ventrolateral prefrontal cortex. *Neuron, 47*(6), 907-918. doi:10.1016/j.neuron.2005.07.023

Badre, D., & Wagner, A. D. (2007). Left ventrolateral prefrontal cortex and the cognitive control of memory. *Neuropsychologia, 45*(13), 2883-2901. doi:10.1016/j.neuropsychologia.2007.06.015

Barredo, J., Oztekin, I., & Badre, D. (2015). Ventral fronto-temporal pathway supporting cognitive control of episodic memory retrieval. *Cereb Cortex, 25*(4), 1004-1019. doi:10.1093/cercor/bht291

Benoit, R. G., & Schacter, D. L. (2015). Specifying the core network supporting episodic simulation and episodic memory by activation likelihood estimation. *Neuropsychologia, 75*, 450-457. doi:10.1016/j.neuropsychologia.2015.06.034

Bowles, R. P., & Salthouse, T. A. (2003). Assessing the age-related effects of proactive interference on working memory tasks using the Rasch model. *Psychol Aging, 18*(3), 608-615. doi:10.1037/0882-7974.18.3.608

Burton, R. L., Lek, I., Dixon, R. A., & Caplan, J. B. (2019). Associative interference in older and younger adults. *Psychol Aging, 34*(4), 558-571. doi:10.1037/pag0000361

Cansino, S., Trejo-Morales, P., Estrada-Manilla, C., Pasaye-Alcaraz, E. H., Aguilar-Castaneda, E., Salgado-Lujambio, P., & Sosa-Ortiz, A. L. (2015). Brain activity during source memory retrieval in young, middle-aged and old adults. *Brain Research*. doi:10.1016/j.brainres.2015.05.032

Carson, N., Leach, L., & Murphy, K. J. (2018). A re-examination of Montreal Cognitive Assessment (MoCA) cutoff scores. *Int J Geriatr Psychiatry, 33*(2), 379-388. doi:10.1002/gps.4756

Connelly, S. L., Hasher, L., & Zacks, R. T. (1991). Age and reading: the impact of distraction. *Psychology and aging, 6*(4), 533-541. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/1777141

Craik, F. (1986). *A functional account of age differences in memory. Human memory and cognitive capabilities: Mechanisms and performances*. Paper presented at the Symposium in Memoriam.

Dale, A. M. (1999). Optimal experimental design for event-related fMRI. *Human Brain Mapping, 8*(2-3), 109-114. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/10524601

de Chastelaine, M., Mattson, J. T., Wang, T. H., Donley, B. E., & Rugg, M. D. (2015). Sensitivity of negative subsequent memory and task-negative effects to age and

associative memory performance. *Brain Research, 1612*, 16-29. doi:10.1016/j.brainres.2014.09.045

de Chastelaine, M., Mattson, J. T., Wang, T. H., Donley, B. E., & Rugg, M. D. (2016). The neural correlates of recollection and retrieval monitoring: Relationships with age and recollection performance. *Neuroimage, 138*, 164-175. doi:10.1016/j.neuroimage.2016.04.071

Dennis, N. A., Hayes, S. M., Prince, S. E., Madden, D. J., Huettel, S. A., & Cabeza, R. (2008). Effects of aging on the neural correlates of successful item and source memory encoding. *J Exp Psychol Learn Mem Cogn, 34*(4), 791-808. doi:2008-08549-007 [pii] 10.1037/0278-7393.34.4.791

Dennis, N. A., Kim, H., & Cabeza, R. (2008). Age-related Differences in Brain Activity during True and False Memory Retrieval. *J Cogn Neurosci*. doi:10.1162/jocn.2008.20096

Dobbins, I. G., Rice, H. J., Wagner, A. D., & Schacter, D. L. (2003). Memory orientation and success: separable neurocognitive components underlying episodic recognition. *Neuropsychologia, 41*(3), 318-333. doi:10.1016/s0028-3932(02)00164-1

Duarte, A., Henson, R. N., & Graham, K. S. (2008). The effects of aging on the neural correlates of subjective and objective recollection. *Cereb Cortex, 18*(9), 2169-2180. doi:bhm243 [pii] 10.1093/cercor/bhm243

Dulas, M. R., & Duarte, A. (2011). The effects of aging on material-independent and material-dependent neural correlates of contextual binding. *Neuroimage, 57*(3), 1192-1204. doi:S1053-8119(11)00544-1 [pii] 10.1016/j.neuroimage.2011.05.036

Dulas, M. R., & Duarte, A. (2012a). The effects of aging on material-independent and material-dependent neural correlates of source memory retrieval. *Cereb Cortex, 22*(1), 37-50. doi:10.1093/cercor/bhr056

Dulas, M. R., & Duarte, A. (2012b). The effects of aging on material-independent and material-dependent neural correlates of source memory retrieval. *Cerebral Cortex, 22*(1), 37-50. doi:10.1093/cercor/bhr056

Dulas, M. R., & Duarte, A. (2013). The influence of directed attention at encoding on source memory retrieval in the young and old: an ERP study. *Brain Res, 1500*, 55-71. doi:10.1016/j.brainres.2013.01.018

Dulas, M. R., & Duarte, A. (2016). Age-related changes in overcoming proactive interference in associative memory: The role of PFC-mediated executive control processes at retrieval. *Neuroimage, 132*, 116-128. doi:10.1016/j.neuroimage.2016.02.017

Ebert, P. L., & Anderson, N. D. (2009). Proactive and retroactive interference in young adults, healthy older adults, and older adults with amnestic mild cognitive impairment. *J Int Neuropsychol Soc, 15*(1), 83-93. doi:10.1017/S1355617708090115

Ebner, N. C., Riediger, M., & Lindenberger, U. (2010). FACES--a database of facial expressions in young, middle-aged, and older women and men: development and validation. *Behav Res Methods, 42*(1), 351-362. doi:10.3758/BRM.42.1.351

Eichenbaum, H., Yonelinas, A. R., & Ranganath, C. (2007). The Medial Temporal Lobe and Recognition Memory. *Annu Rev Neurosci*.

Emery, L., Hale, S., & Myerson, J. (2008). Age differences in proactive interference, working memory, and abstract reasoning. *Psychol Aging, 23*(3), 634-645. doi:10.1037/a0012577

Faust, M. E., Balota, D. A., Spieler, D. H., & Ferraro, F. R. (1999). Individual differences in information-processing rate and amount: implications for group differences in response latency. *Psychol Bull, 125*(6), 777-799. doi:10.1037/0033-2909.125.6.777

Feredoes, E., Heinen, K., Weiskopf, N., Ruff, C., & Driver, J. (2011). Causal evidence for frontal involvement in memory target maintenance by posterior brain areas during distracter interference of visual working memory. *Proc Natl Acad Sci U S A, 108*(42), 17510-17515. doi:10.1073/pnas.1106439108

Fletcher, P. C., & Henson, R. N. (2001). Frontal lobes and human memory: insights from functional neuroimaging. *Brain, 124*(Pt 5), 849-881.

Fletcher, P. C., Shallice, T., & Dolan, R. J. (2000). "Sculpting the response space"--an account of left prefrontal activation at encoding. *Neuroimage, 12*(4), 404-417. doi:10.1006/nimg.2000.0633

Friedman, D. (2000). Event-related brain potential investigations of memory and aging. *Biol Psychol, 54*(1-3), 175-206.

Glisky, E. L., & Kong, L. L. (2008). Do young and older adults rely on different processes in source memory tasks? A neuropsychological study. *J Exp Psychol Learn Mem Cogn, 34*(4), 809-822. doi:10.1037/0278-7393.34.4.809

Glisky, E. L., Rubin, S. R., & Davidson, P. S. (2001). Source memory in older adults: an encoding or retrieval problem? *J Exp Psychol Learn Mem Cogn, 27*(5), 1131-1146. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/11550742

Greenwood, P. M. (2000). The frontal aging hypothesis evaluated. *J Int Neuropsychol Soc, 6*(6), 705-726. Retrieved from http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve&db=PubMed&dopt=Citation&list_uids=11011517

Guez, J., & Naveh-Benjamin, M. (2016). Proactive interference and concurrent inhibitory processes do not differentially affect item and associative recognition: Implication for the age-related associative memory deficit. *Memory, 24*(8), 1091-1107. doi:10.1080/09658211.2015.1069852

Hartman, M., & Hasher, L. (1991). Aging and suppression: memory for previously relevant information. *Psychol Aging, 6*(4), 587-594. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/1777147

Hasher, L., Quig, M. B., & May, C. P. (1997). Inhibitory control over no-longer-relevant information: adult age differences. *Memory & cognition, 25*(3), 286-295. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/9184480

Haxby, J. V. (2012). Multivariate pattern analysis of fMRI: the early beginnings. *Neuroimage, 62*(2), 852-855. doi:10.1016/j.neuroimage.2012.03.016

Hay, J. F., & Jacoby, L. L. (1999). Separating habit and recollection in young and older adults: effects of elaborative processing and distinctiveness. *Psychol Aging, 14*(1), 122-134. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/10224637

Healey, M. K., Hasher, L., & Campbell, K. L. (2013). The role of suppression in resolving interference: evidence for an age-related deficit. *Psychol Aging, 28*(3), 721-728. doi:10.1037/a0033003

Henson, R. N., Rugg, M. D., Shallice, T., & Dolan, R. J. (2000). Confidence in recognition memory for words: dissociating right prefrontal roles in episodic retrieval. *J Cogn Neurosci, 12*(6), 913-923.

Henson, R. N., Shallice, T., & Dolan, R. J. (1999). Right prefrontal cortex and episodic memory retrieval: a functional MRI test of the monitoring hypothesis. *Brain, 122 (Pt 7)*, 1367-1381.

Ikier, S., Yang, L., & Hasher, L. (2008). Implicit proactive interference, age, and automatic versus controlled retrieval strategies. *Psychol Sci, 19*(5), 456-461. doi:10.1111/j.1467-9280.2008.02109.x

Jacoby, L. L., Bishara, A. J., Hessels, S., & Toth, J. P. (2005). Aging, subjective experience, and cognitive control: dramatic false remembering by older adults. *J Exp Psychol Gen, 134*(2), 131-148.

Jonides, J., Marshuetz, C., Smith, E. E., Reuter-Lorenz, P. A., Koeppe, R. A., & Hartley, A. (2000). Age differences in behavior and PET activation reveal differences in interference resolution in verbal working memory. *J Cogn Neurosci, 12*(1), 188-196. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/10769315

Jonides, J., & Nee, D. E. (2006). Brain mechanisms of proactive interference in working memory. *Neuroscience, 139*(1), 181-193. doi:10.1016/j.neuroscience.2005.06.042

Kuhl, B. A., Bainbridge, W. A., & Chun, M. M. (2012). Neural reactivation reveals mechanisms for updating memory. *J Neurosci, 32*(10), 3453-3461. doi:10.1523/JNEUROSCI.5846-11.2012

Kuhl, B. A., Rissman, J., Chun, M. M., & Wagner, A. D. (2011). Fidelity of neural reactivation reveals competition between memories. *Proc Natl Acad Sci U S A, 108*(14), 5903-5908. doi:10.1073/pnas.1016939108

Lepage, M., Brodeur, M., & Bourgouin, P. (2003). Prefrontal cortex contribution to associative recognition memory in humans: an event-related functional magnetic resonance imaging study. *Neurosci Lett, 346*(1-2), 73-76. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/12850551

Li, J., Morcom, A. M., & Rugg, M. D. (2004). The effects of age on the neural correlates of successful episodic retrieval: an ERP study. *Cogn Affect Behav Neurosci, 4*(3), 279-293.

Lustig, C., & Jantz, T. (2015). Questions of age differences in interference control: When and how, not if? *Brain Res, 1612*, 59-69. doi:10.1016/j.brainres.2014.10.024

Lustig, C., May, C. P., & Hasher, L. (2001). Working memory span and the role of proactive interference. *J Exp Psychol Gen, 130*(2), 199-207. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/11409099

Manly, J. J. (2005). Advantages and disadvantages of separate norms for African Americans. *Clin Neuropsychol, 19*(2), 270-275. doi:10.1080/13854040590945346

May, C. P., Hasher, L., & Kane, M. J. (1999). The role of interference in memory span. *Mem Cognit, 27*(5), 759-767. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/10540805

McDonough, I. M., & Gallo, D. A. (2013a). Impaired retrieval monitoring for past and future autobiographical events in older adults. *Psychology and Aging, 28*(2), 457-466. doi:10.1037/a0032732

McDonough, I. M., & Gallo, D. A. (2013b). Impaired retrieval monitoring for past and future autobiographical events in older adults. *Psychol Aging, 28*(2), 457-466. doi:10.1037/a0032732

Miller, E. K. (2000). The prefrontal cortex and cognitive control. *Nat Rev Neurosci, 1*(1), 59-65. doi:10.1038/35036228

Mitchell, K. J., & Johnson, M. K. (2009). Source monitoring 15 years later: what have we learned from fMRI about the neural mechanisms of source memory? *Psychol Bull, 135*(4), 638-677. doi:2009-09537-007 [pii] 10.1037/a0015849

Mitchell, K. J., Johnson, M. K., Raye, C. L., & Greene, E. J. (2004). Prefrontal cortex activity associated with source monitoring in a working memory task. *J Cogn Neurosci, 16*(6), 921-934.

Moss, H. E., Abdallah, S., Fletcher, P., Bright, P., Pilgrim, L., Acres, K., & Tyler, L. K. (2005). Selecting among competing alternatives: selection and retrieval in the left

inferior frontal gyrus. *Cereb Cortex, 15*(11), 1723-1735. doi:10.1093/cercor/bhi049

Nasreddine, Z. S., Phillips, N. A., Bedirian, V., Charbonneau, S., Whitehead, V., Collin, I., . . . Chertkow, H. (2005). The Montreal Cognitive Assessment, MoCA: a brief screening tool for mild cognitive impairment. *J Am Geriatr Soc, 53*(4), 695-699. doi:10.1111/j.1532-5415.2005.53221.x

Naveh-Benjamin, M., Brav, T. K., & Levy, O. (2007). The associative memory deficit of older adults: the role of strategy utilization. *Psychol Aging, 22*(1), 202-208. doi:10.1037/0882-7974.22.1.202

Nelson, J. K., Reuter-Lorenz, P. A., Persson, J., Sylvester, C. Y., & Jonides, J. (2009). Mapping interference resolution across task domains: a shared control process in left inferior frontal gyrus. *Brain Res, 1256*, 92-100. doi:10.1016/j.brainres.2008.12.001

Norman, K. A., Polyn, S. M., Detre, G. J., & Haxby, J. V. (2006). Beyond mind-reading: multi-voxel pattern analysis of fMRI data. *Trends Cogn Sci, 10*(9), 424-430. doi:10.1016/j.tics.2006.07.005

Nyberg, L., Salami, A., Andersson, M., Eriksson, J., Kalpouzos, G., Kauppi, K., . . . Nilsson, L. G. (2010). Longitudinal evidence for diminished frontal cortex function in aging. *Proceedings of the National Academy of Sciences of the United States of America, 107*(52), 22682-22686. doi:10.1073/pnas.1012651108

Oren, N., Shapira-Lichter, I., Lerner, Y., Tarrasch, R., Hendler, T., Giladi, N., & Ash, E. L. (2017). Schema benefit vs. proactive interference: Contradicting behavioral outcomes and coexisting neural patterns. *Neuroimage, 158*, 271-281. doi:10.1016/j.neuroimage.2017.07.006

Oztekin, I., Curtis, C. E., & McElree, B. (2009). The medial temporal lobe and the left inferior prefrontal cortex jointly support interference resolution in verbal working memory. *J Cogn Neurosci, 21*(10), 1967-1979. doi:10.1162/jocn.2008.21146

Paxton, J. L., Barch, D. M., Racine, C. A., & Braver, T. S. (2008). Cognitive control, goal maintenance, and prefrontal function in healthy aging. *Cereb Cortex, 18*(5), 1010-1028. doi:bhm135 [pii] 10.1093/cercor/bhm135

Pereira, J. M., Xiong, L., Acosta-Cabronero, J., Pengas, G., Williams, G. B., & Nestor, P. J. (2010). Registration accuracy for VBM studies varies according to region and degenerative disease grouping. *Neuroimage, 49*(3), 2205-2215. doi:S1053-8119(09)01139-2 [pii] 10.1016/j.neuroimage.2009.10.068

Pettigrew, C., & Martin, R. C. (2014). Cognitive declines in healthy aging: evidence from multiple aspects of interference resolution. *Psychol Aging, 29*(2), 187-204. doi:10.1037/a0036085

Raz, N., Gunning, F. M., Head, D., Dupuis, J. H., McQuain, J., Briggs, S. D., . . . Acker, J. D. (1997). Selective aging of the human cerebral cortex observed in vivo: differential vulnerability of the prefrontal gray matter. *Cereb Cortex, 7*(3), 268-282.

Raz, N., & Kennedy, K. M. (2009). A systems approach to the aging brain: neuroanatomic changes, their modifiers, and cognitive correlates. In W. J. Jagust & M. D'Esposito (Eds.), *Imaging the Aging Brain*: Oxford University Press.

Reuter-Lorenz, P. A., & Cappell, K. A. (2008). Neurocognitive aging and the compensation hypothesis. *Current Directions in Psychological Science, 17*, 177–182.

Reuter-Lorenz, P. A., & Lustig, C. (2005). Brain aging: reorganizing discoveries about the aging mind. *Curr Opin Neurobiol, 15*(2), 245-251. doi:10.1016/j.conb.2005.03.016

Rugg, M. D., Henson, R. N., & Robb, W. G. (2003). Neural correlates of retrieval processing in the prefrontal cortex during recognition and exclusion tasks. *Neuropsychologia, 41*(1), 40-52.

Rugg, M. D., & Morcom, A. M. (2005). The Relationship between Brain Activity, Cognitive Performance and Aging: The

Case of Memory. In R. Cabeza, L. Nyberg, & D. C. Park (Eds.), *Cognitive neuroscience of aging: Linking cognitive and cerebral aging*.

Sestieri, C., Shulman, G. L., & Corbetta, M. (2017). The contribution of the human posterior parietal cortex to episodic memory. *Nat Rev Neurosci, 18*(3), 183-192. doi:10.1038/nrn.2017.6

Shallice, T., Fletcher, P., Frith, C. D., Grasby, P., Frackowiak, R. S., & Dolan, R. J. (1994). Brain regions associated with acquisition and retrieval of verbal episodic memory. *Nature, 368*(6472), 633-635. doi:10.1038/368633a0

Simons, J. S., & Spiers, H. J. (2003). Prefrontal and medial temporal lobe interactions in long-term memory. *Nature reviews. Neuroscience, 4*(8), 637-648. doi:10.1038/nrn1178

Sink, K. M., Craft, S., Smith, S. C., Maldjian, J. A., Bowden, D. W., Xu, J., . . . Divers, J. (2015). Montreal Cognitive Assessment and Modified Mini Mental State Examination in African Americans. *J Aging Res, 2015*, 872018. doi:10.1155/2015/872018

Slotnick, S. D., Moo, L. R., Segal, J. B., & Hart, J., Jr. (2003). Distinct prefrontal cortex activity associated with item memory and source memory for visual shapes. *Brain Res Cogn Brain Res, 17*(1), 75-82. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/12763194

Stark, C. E., & Squire, L. R. (2001). When zero is not zero: the problem of ambiguous baseline conditions in fMRI. *Proc Natl Acad Sci U S A, 98*(22), 12760-12766.

Stern PC, Carstensen LL, & editors. (2000). *National Research Council (US) Committee on Future Directions for Cognitive Research on Aging: The Aging Mind: Opportunities in Cognitive Research.* Retrieved from Washington (DC): https://www.ncbi.nlm.nih.gov/books/NBK44823/

Thakral, P. P., Wang, T. H., & Rugg, M. D. (2017). Decoding the content of recollection within the core recollection network and beyond. *Cortex, 91*, 101-113. doi:10.1016/j.cortex.2016.12.011

Thompson-Schill, S. L., Jonides, J., Marshuetz, C., Smith, E. E., D'Esposito, M., Kan, I. P., . . . Swick, D. (2002). Effects of frontal lobe damage on interference effects in working memory. *Cogn Affect Behav Neurosci, 2*(2), 109-120. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/12455679

Wahlheim, C. N. (2014). Proactive effects of memory in young and older adults: the role of change recollection. *Mem Cognit, 42*(6), 950-964. doi:10.3758/s13421-014-0411-4

Wais, P. E., Kim, O. Y., & Gazzaley, A. (2012). Distractibility during episodic retrieval is exacerbated by perturbation of left ventrolateral prefrontal cortex. *Cereb Cortex, 22*(3), 717-724. doi:10.1093/cercor/bhr160

West, R. L. (1996). An application of prefrontal cortex function theory to cognitive aging. *Psychol Bull, 120*(2), 272-292.

Xiao, J., Hays, J., Ehinger, K., Oliva, A., & Torralba, A. (2010). SUN Database: Large-scale Scene Recognition from Abbey to Zoo. *International Journal of Computer Vision, 119*(1), 3-22.

Yassa, M. A., & Stark, C. E. (2009). A quantitative evaluation of cross-participant registration techniques for MRI studies of the medial temporal lobe. *Neuroimage, 44*(2), 319-327. doi:S1053-8119(08)01022-7 [pii]

Yonelinas, A. P. (2002). The nature of recollection and familiarity: A review of 30 years of research. *Journal of memory and language, 46*(3), 441-517.